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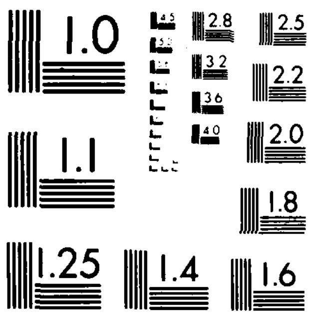

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

CAUSES AND CORRECTIONS FOR PROPELLER-EXCITED AIRBORNE NOISE ON A NAVAL AUXILIARY OILER

by

Michael B. Wilson, Donald N. McCallum
Robert J. Boswell, David D. Bernhard
and
Alan B. Chase

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Presented at the Annual Meeting of
The Society of Naval Architects and Marine Engineers
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RESEARCH AND DEVELOPMENT REPORT

November 1983

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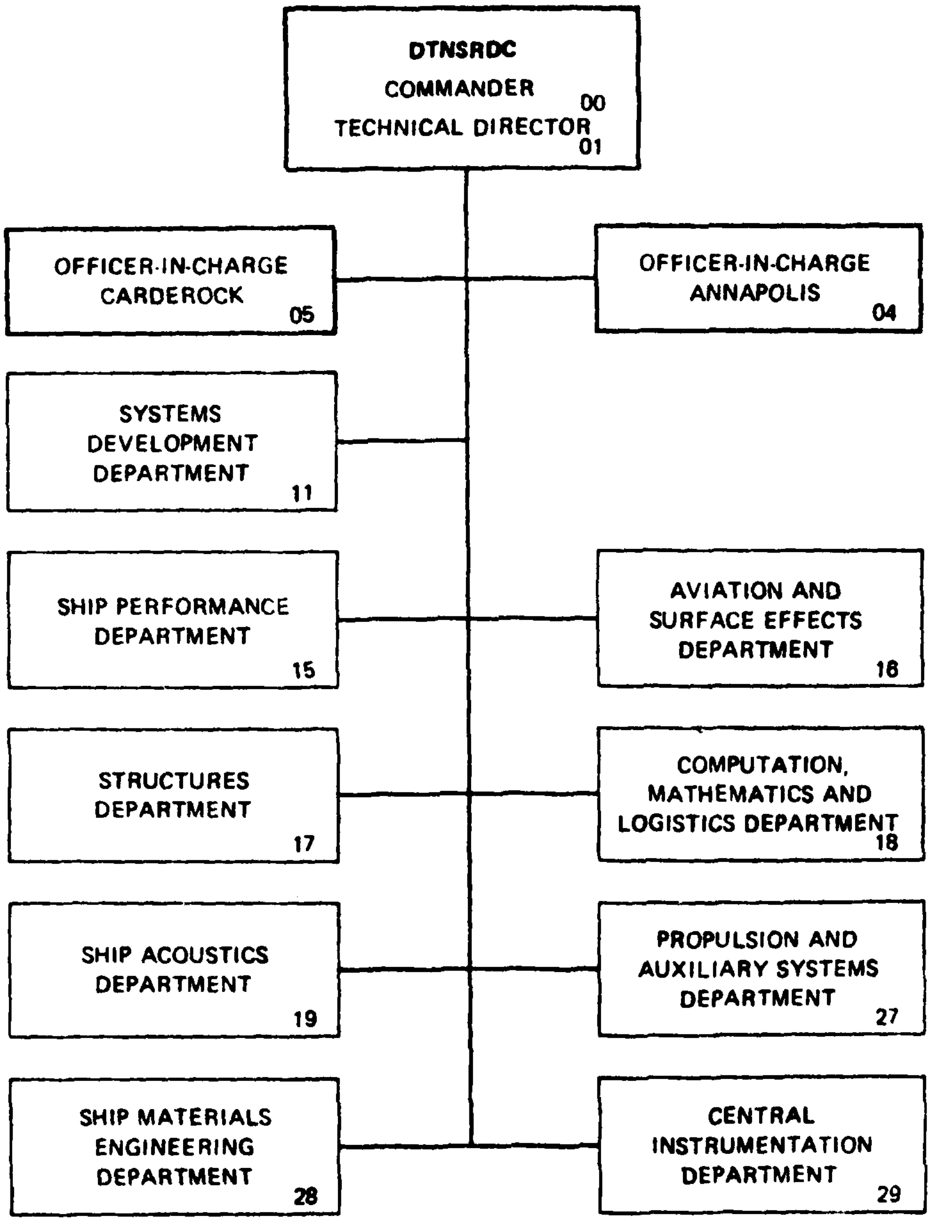

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The AO-177, first of a new class of Naval Auxiliary Oilers, experienced high levels of inboard airborne noise and initial-stage erosion damage on its skewed, seven-bladed propeller during builder's trials. This report describes the problems, corrective design modifications considered, and procedures and rationale used to develop a successful corrective design modification consisting of a fin to improve the flow into the propeller. To evaluate the

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problem, extensive model experiments were conducted, including flow visualization, wake survey, powering experiments, and a crucial series of cavitation experiments including propeller-induced hull pressure measurements in a large water tunnel. Experiments with two fin designs showed the superiority of a flow-accelerating configuration. Other experiments showed some benefits of altering the propeller blade shape. Propeller analyses were undertaken to provide design alternatives for retrofitting the ship with a new propeller. A full-scale trial with the final fin design provided evidence of a reduction of the highest levels of airborne noise, reduction in the initial-stage erosion damage, and minimal effect on ship speed. The result is that the AO-177 has been accepted by the fleet for normal service.

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ADMINISTRATIVE INFORMATION

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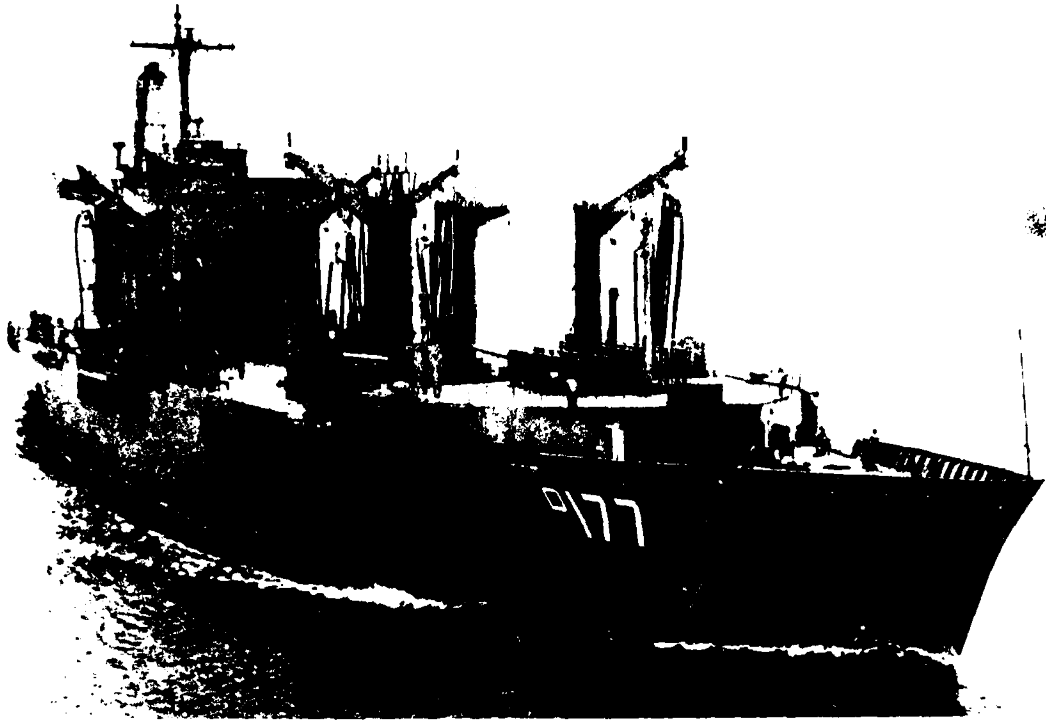

The Naval Auxiliary Oiler AO-177, USS *Cimarron* (U.S. Navy Photograph)

Causes and Corrections for Propeller-Excited Airborne Noise on a Naval Auxiliary Oiler

Michael B. Wilson,[1] Member, **Donald N. McCallum,**[2] Associate Member,
Robert J. Boswell,[1] Member, **David D. Bernhard,**[3] Visitor, and **Alan B. Chase,**[3] Visitor

The AO-177, first of a new class of Naval Auxiliary Oilers, experienced high levels of inboard airborne noise and initial-stage erosion damage on its skewed, seven-bladed propeller during builder's trials. This paper describes the problems, corrective design modifications considered, and procedures and rationale used to develop a successful corrective design modification consisting of a fin to improve the flow into the propeller. To evaluate the problem, extensive model experiments were conducted, including flow visualization, wake surveys, powering experiments, and a crucial series of cavitation experiments including propeller-induced hull pressure measurements in a large water tunnel. Experiments with two fin designs showed the superiority of a flow-accelerating configuration. Other experiments showed some benefits of altering the propeller blade shape. Propeller analyses were undertaken to provide design alternatives for retrofitting the ship with a new propeller. A full-scale trial with the final fin design provided evidence of a reduction of the highest levels of airborne noise, reduction in the initial-stage erosion damage, and minimal effect on ship speed. The result is that the AO-177 has been accepted by the fleet for normal service.

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Presented at the Annual Meeting, New York, N. Y., November 17–20, 1982, of THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS.

The views expressed herein are the opinions of the authors and not necessarily those of DOD or the Department of the Navy.

Introduction

IN RECENT YEARS there has been a rash of propeller-induced vibration and noise problems that have plagued certain types of commercial ships (usually of single-screw design). This has been the result of the increase of power per shaft, restrictive demands on stern geometry and propeller and shafting placements, tendencies toward high block coefficients and large beam-to-draft ratios, and trends toward single-screw designs for fuel economy. These problems normally manifest themselves in the form of unacceptable hull girder vibration in the stern region near the propeller and at the upper levels of deckhouses, structural damage from fatigue, and considerable crew nuisance, often resulting in imposed speed limitations. Although the U.S. Navy has had a minimal number of such occurrences with its single-screw auxiliary ships, there was an exception in the case of the recently completed AO-177, the first ship of a new class of Naval Auxiliary Oilers. During builder's trials, the USS *Cimarron* (AO-177) was reported to have unacceptably high levels of airborne noise and localized vibration. Close inspection revealed early stage (incubation zone) propeller erosion damage and bent trailing edges near the tips of all seven blades of the propeller. Based on these full-scale findings, the Navy immediately embarked on a corrective program to identify the root cause of the difficulties, develop a suitable solution, and verify that the resulting modification did indeed cure the problems. In the process of satisfying these objectives, the Naval Sea Systems Command (NAVSEA) together with the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) employed the services of the Swedish Maritime Research Centre (SSPA), Hydronautics, Inc. (HNI), Det norske Veritas (DnV), and several independent experts in the field of ship hydrodynamics analysis. This paper documents the problems, the experiences, the solutions proposed, the model experiments, and analytical predictions carried out for a number of alternative proposed solutions, culminating in the final choice of a wake improving fin design and its validation with a full-scale trial.

Since 1952, when Baier [1][1] designed the first wake modifying and anti-air-drawing fin for use in curing severe tantal vibrations of the Great Lakes ore carrier *Carl D. Bradley*, variations of this type of stern appendage have been employed (usually successfully) to help improve the flow into the propeller region of many kinds of single-screw ships. Most of the applications of such a fin have been on full block ships such as tankers, roll-on/roll-off (RO/RO) ships, containerships, liquefied natural gas (LNG) vessels, and other bulk and product carriers [2, 3]. In most instances the effect of the fin is to divert flow into the propeller disk region, firming up slow-moving or separating boundary-layer flows in the afterbody region, generally reducing the large wake peak at the top of the disk, and thereby reducing the large flow angle excursions at the outer radii of the propeller blades. These changes apparently reduce the vibration excitation levels by reducing the fluctuating pressures induced on the hull (and resulting fluctuating hull surface forces) that arise from intermittent propeller blade cavitation, rather than by significantly reducing the bearing force excitation levels.

As will be shown in the case of the AO-177, there were possible improvements of the hull surface excitation to be achieved with alternative propeller designs as well as with the wake modification. Part of the objective of the investigation described here was to identify a corrective measure that was effective enough to do the job, yet simple enough to be deployed and verified quickly.

[1] Numbers in brackets designate References at end of paper.

The ship and propeller

Main particulars

The AO-177 (USS *Cimarron*) is the first of a new class of single screw Naval Auxiliary Oilers designed by the U.S. Navy and built at Avondale Shipyards, Inc. in New Orleans, Louisiana. Its principal particulars are given in Table 1.

From the body plan lines and profile outlines given in Fig. 1, it can be seen that the ship hull has a prominent elliptical bulbous bow, rather narrow V-section shapes toward the after end, a clearwater stern, and generous propeller clearances both vertically and forward to the hull surface. The propeller clearances defined in the figure are

$$a_2/D = 0.2915$$

$$a_x/D = 0.5503 \text{ (at } 0.8R\text{)}$$

$$a_{xt}/D = 0.519 \text{ (at tip)}$$

$$b_{xt}/D = 0.192 \text{ (at tip)}$$

Some care was taken during the design stages to produce a hull design with good resistance characteristics, and [illegible] effort succeeded to a great extent because the AO-177 has [illegible] able power-to-weight ratio compared with similar ship[illegible] at the same speed. Purposeful slimming of the hull lines at [illegible] nitely contributed to the good resistance properties of th[illegible] 77. Yet, these narrow aft section shapes have been dete[illegible] ed to be largely responsible for the poor wake (rather dee[illegible] -like main wake shadow). It must be noted that desig[illegible] ll shape for the AO-177 was determined at a time whe[illegible] as much more fragmentary understanding of the [illegible] ntial problems that could arise from intermittent propeller cavitation, and most of the concern then was focused on full block hull shapes.

Figure 2 shows a simplified inboard profile of the after end of the ship.

Propeller details and design

The main propeller particulars are presented in Table 2. This propeller was designed to meet the conditions outlined in Table 3. The design process is discussed in detail in reference [4] and is essentially the same as the process described in reference [5].

Upon making the required tradeoffs to meet the conditions specified in Table 3, it turned out that the geometry of the propeller was controlled largely by the requirement that the longitudinal and torsional vibration in the main propulsion system be below that specified in MIL-STD 167 [6] and that hull vibration levels meet the requirements of MIL-STD 1472 [7]. These specifications resulted in requirements which were more restrictive than those imposed by other design specifications and, therefore, controlled the selection of the number of blades, propeller diameter, magnitude and radial distribution of skew, and radial distribution of chord length.

Based on a preliminary longitudinal and torsional vibration response analysis of the main propulsion system that was available at the time of the propeller design (1975), which included only a rough estimate of the stiffness of the thrust bearing, it was concluded that a six-bladed propeller should not be used because blade frequency for a six-bladed propeller would coincide with a predicted longitudinal resonance at the full power point, that is, at approximately 100 × 6/60 = 10 Hz. The vibration analysis of the main propulsion system also indicated that the blade frequency thrust at full power must be less than 13.3 kN (3000 lb), that is, less than 1 percent of the time-average thrust, for either a five- or seven-bladed propeller. For this propulsion system the upper limit on blade frequency

Table 1 Main ship particulars

	SI	U.S. Customary
Length overall, L_{OA}	[illegible]	[illegible]
Length on waterline, L_{WL}	[illegible]	[illegible]
Length between perpendiculars, L_{PP}	[illegible]	[illegible]
Beam, B	[illegible]	[illegible]
Depth to main deck, D_{M}	[illegible]	[illegible]
Draft, design full load (mean), T	[illegible]	[illegible]
Draft trial (mean), T	[illegible]	[illegible]
Draft ballast (mean), T	[illegible]	[illegible]
Trim, design full load (down by stern)	[illegible]	[illegible]
Trim, trial full load (down by bow)	[illegible]	[illegible]
Trim, ballast (down by stern)	[illegible]	[illegible]
Displacement, design full load, Δ(SW)	[illegible]	[illegible]
Displacement, trial full load, Δ(SW)	[illegible]	[illegible]
Displacement, ballast, Δ(SW)	[illegible]	[illegible]
Block coefficient design, C_B	[illegible]	[illegible]
Displacement length ratio, Δ	[illegible]	[illegible]
Full power design	[illegible] kW	[illegible]
Design ship speed (endurance speed)	20 knots	[illegible]
Maximum speed (full power)	[illegible] knots	[illegible] knots

thrust was much more restrictive than the upper limit on blade frequency torque; that is, any propeller for the AO-177 that has blade frequency thrust below the allowable limit will automatically have blade frequency torque below the allowable limit based on available calculation procedures. The blade frequency side forces and bending moments do not enter the vibratory requirements of the main propulsion system explicitly; however, the transverse forces could, if large in amplitude or near a resonant frequency, excite hull vibration. Therefore, it was required that the vertical and transverse (horizontal) components of blade frequency bearing force at full power be less than 8.9 kN (2000 lb).

A four-bladed propeller was rejected because of possible excessive hull girder vibration at blade rate frequency and possible longitudinal shaft resonance problems at twice blade rate frequency. The conclusion that the hull girder vibration

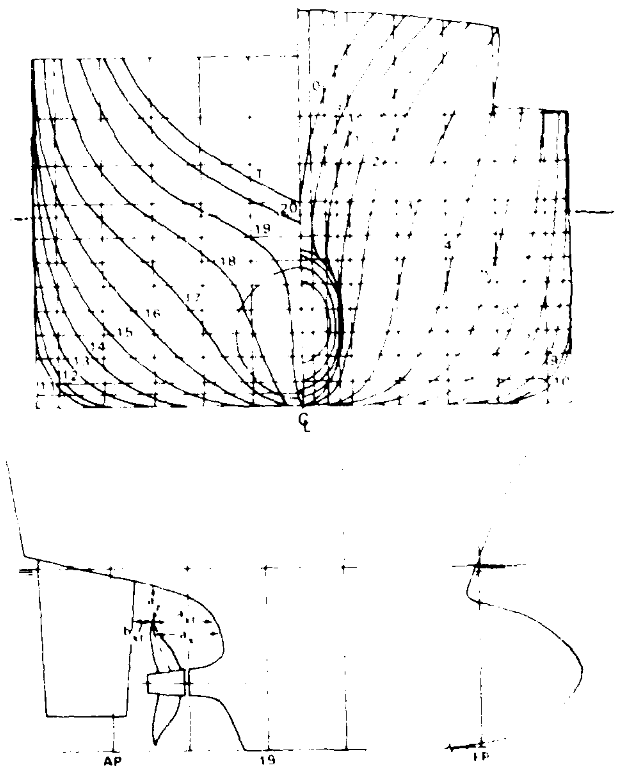


Fig. 1 Body plan and bow and stern profiles

could be excessive with four blades was based on design stage calculations of hull vibration responses with excitation empirically derived from comparison of calculated and measured amplitudes of this type of vibration on similar U.S. Navy ships, on previous experience with this type of vibration on similar U.S. Navy ships with four-bladed propellers, and on the phenomenon that this vibratory response tends to increase as excitation frequency decreases. At the time of the propeller design, it was concluded that similar problems were possible but less probable, with a five-bladed propeller. This alone was not justification for immediately rejecting a five-bladed propeller, but the probability of hull girder vibration would be considered in any possible design tradeoffs for selecting the number of blades.

Requirements of MIL-STD 167 are that for all operating conditions the peak periodic thrust amplitude at the thrust bearing be less than the lesser of

1. the time-average thrust at the local operating point, or
2. one-half the time-average thrust at full-power steady ahead.

The following empirical multiplicative factors derived from

Nomenclature

A_E = expanded area of propeller $Z\int_{r_h}^{R} c\,dr$
A_o = disk area of propeller πR^2
A_P = projected area of propeller
a_x = propeller clearance, horizontal distance between blade reference line and hull at $0.8R$
a_{xt} = propeller horizontal clearance forward to hull at tip
a_z = vertical tip clearance between propeller and hull
B = beam of ship
b_{xt} = propeller horizontal clearance aft to rudder at tip
C_B = block coefficient
C_{Th} = thrust loading coefficient
$c(x_R)$ = propeller blade section chord length
D = propeller diameter
D_H = depth of hull, keel to main deck
dB = decibel sound pressure level in octave band $20\log(\bar{p}/20\mu Pa)$
$F_{x/Z}$ = amplitude of blade frequency harmonic of axial bearing force (thrust)
$F_{y/Z}$ = amplitude of blade frequency harmonic of transverse horizontal bearing force
$F_{z/Z}$ = amplitude of blade frequency harmonic of vertical bearing force
$F_{Sx/Z}$ = amplitude of blade frequency harmonic of axial hull surface force
$F_{Sy/Z}$ = amplitude of blade frequency harmonic of transverse horizontal hull surface force
$F_{Sz/Z}$ = amplitude of blade frequency harmonic of vertical hull surface force
F_n = Froude number
$f(x_R)$ = camber of propeller blade section
g = acceleration due to gravity
H = head, distance from propeller centerline to water surface plus atmospheric pressure minus vapor pressure
$i_T(x_R)$ = rake of propeller blade section
J = advance coefficient $J = V_A/nD$
K = pressure amplitude factor, see Fig. 18
L = length
L_{OA} = length overall
L_{PP} = length between perpendiculars
L_{WL} or L = length on waterline
n = propeller revolutions per unit time
$P(x_R)$ = propeller section pitch
P_D = delivered power at propeller $2\pi nQ$
P_E = effective power
$\bar{p}$ = root mean square (rms) sound pressure level in specified bandwidth
R = radius of propeller
r = radial distance from propeller axis
r_h = radius of propeller hub
T = thrust
T_m = draft, mean
t = thrust deduction fraction
$t(x_R)$ = thickness of propeller blade section
V = ship speed
V_A = speed of advance $V(1-w_T)$
$V_R(x_R,\theta_w)/V$ = radial velocity component ratio in propeller plane
$V_T(x_R,\theta_w)/V$ = tangential velocity component ratio in propeller plane
$V_X(x_R,\theta_w)/V$ = axial velocity component ratio in propeller plane
V_{X_n}/V = amplitude of nth harmonic of axial velocity component ratio in propeller plane $= 1/\pi \int_0^{2\pi} (V_X(\theta)/V)\cos n\theta\,d\theta$
v_s = single amplitude vibration velocity (rms)
w_T = Taylor wake fraction
x_R = nondimensional radius of propeller blade section, r/R
Z = number of propeller blades
Δ = displacement mass
Δp_Z = blade frequency amplitude of hull surface pressure
Δp_{2Z} = twice blade frequency amplitude of hull surface pressure
∇ = displacement volume
η_D = propulsive efficiency P_E/P_D
η_H = hull efficiency $(1-t)/(1-w_T)$
η_R = relative rotative efficiency
θ_S = skew angle in projected plane of propeller measured from a radial line through midchord of section at hub to radial line through midchord of section at local radius, positive in counterclockwise direction looking upstream
θ_w = wake position angle about propeller axis in propeller plane, measured counterclockwise from upward vertical looking forward $= -\varphi$
λ = linear scale ratio
ρ = mass density of water
σ = cavitation number at shaft centerline based on speed of advance $2gH/V_A^2$
Φ = phase angle
φ = position angle about propeller axis, measured clockwise from upward vertical looking forward $= -\theta_w$

Abbreviations

BBN — Bolt, Beranek and Newman, Inc.
DL — Davidson Laboratory
DnV — Det norske Veritas
DTNSRDC — David W. Taylor Naval Ship Research and Development Center
HI — Hydromechanics, Inc.
HNI — Hydronautics, Inc.
ISO — International Standards Organization
MIT — Massachusetts Institute of Technology
NAVSEA — Naval Sea Systems Command
SSPA — Statens Skeppsprovningsanstalt (Swedish Maritime Research Centre)
VAI — Vorus and Associates, Inc.

full-scale measurements on U. S. Navy ships are applied to the values that are calculated by numerical procedures based on propeller unsteady lifting surface theory [8] including the influences of propeller geometry, propeller operating conditions, model nominal wake patterns, and calculated amplification in the shafting.

1. A factor of 3 for amplitude modulation of the periodic thrust $F_{x,n}$ where $n = Z, 2Z, 3Z$ etc. This modulation may result from a combination of large scale turbulence in the wake, periodic time variation of the wake for steady ship conditions, periodic variation of the wake due to sea waves and ship motions, and small changes in rudder angle for course correction. It is assumed that for each n the calculated amplitude is the minimum amplitude of the modulated signal.

2. A factor of 3 for increase in $(F_{x,n})_T$ at speeds from 90 to 100 percent of full speed, which may be due to the influence of cavitation or change in the wake pattern due to free surface (wavemaking) effects. It is assumed that the calculated amplitude corresponds to $(F_{x,n})_T$ before this increase.

3. A factor of 3 for increase in $(F_x)_n$ in hard (full rudder) turns relative to the $(F_{x,n})$ for the steady ahead condition at any speed. The differences between $(F_x)_n$ in hard turns and $(F_x)_n$ for steady ahead operation results from the different wake patterns, ship speeds, propeller rotational speeds, and extent of cavitation for these conditions. The manner in which these various quantities change from steady ahead to hard turns

[8] As described in a report of restricted distribution by A. Zaloumis and G. P. Antonides entitled "Recent Developments on Longitudinal Vibrations of Surface Ship Propulsion Systems," Sept. 1970.

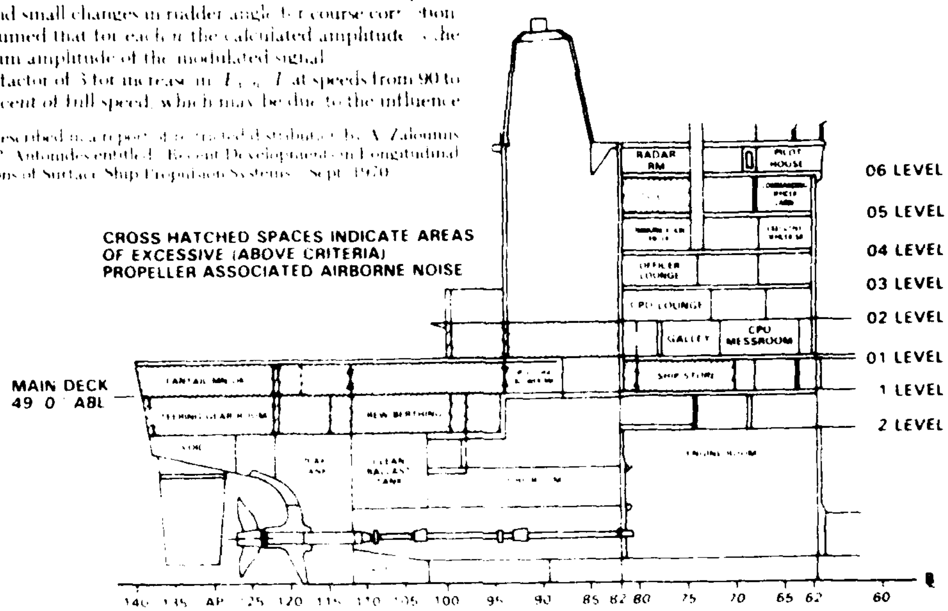
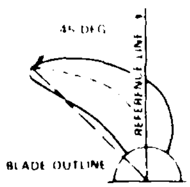


Fig. 2 Inboard profile of stern

Table 2 AO-177 propeller characteristics

Diameter [illegible]	[illegible]
Number of blades, Z	[illegible]
Expanded area ratio, A_E/A_0	[illegible]
Projected area ratio, A_P/A_0	[illegible]
Projected skew angle [illegible]	[illegible]
Pitch to diameter ratio at 0.7R	[illegible]
Section thickness form	NACA 66 (DTNSRDC modified)
Section meanline	NACA [illegible]
[illegible]	[illegible] kN ([illegible] lb)
[illegible]	[illegible]
[illegible]	
Rotation	right hand
Material	Ni-Al Bronze
Weight	[illegible] kg ([illegible] lb)



Radius Ratio r/R	Chord Ratio c/D	Pitch Ratio, P/D	Skew θ_s (deg)	Thickness Ratio t/c	Camber Ratio f/c	Rake Ratio i_r/D
[illegible]	[illegible]	[illegible]	0.0	0.2000	0.0490	0.0000
[illegible]	[illegible]	1.223	[illegible]	0.1625	0.0444	−0.0017
0.4	[illegible]	[illegible]	[illegible]	0.1325	0.0367	−0.0044
0.5	0.2817	1.318	13.3	0.1080	0.0314	−0.0070
0.6	0.2684	1.309	20.0	0.0880	0.0300	−0.0077
0.7	0.2320	1.250	27.2	0.0715	0.0295	−0.0049
0.8	0.1815	1.140	34.5	0.0590	0.0281	−0.0003
0.9	0.1180	0.970	40.3	0.0500	0.0263	0.0082
1.0	0.0000	0.722	45.0	0.0450	0.0240	0.0245

Table 3 Propeller design conditions

Design point	full power at full load displacement
Diameter	6.4 to 7.3 m (21 to 24 ft)
RPS	1.66 at the design point
Endurance	20 knots at 80 percent power
Cavitation criteria	10 percent speed margin on the inception of back bubble at the design point. Other forms of cavitation to be minimized to the extent practicable
Blade skew	Use the amount practicable in order to reduce vibration excitation forces imparted to the propulsion machinery and hull in order to meet MIL-STD-167 and MIL-STD-1472. This dictated the following limits on blade frequency bearing forces: $F_x \leq 13.3$ kN (3000 lb); $(F_y) \leq 8.9$ kN (2000 lb); $(F_z) \leq 8.9$ kN (2000 lb)

especially the wake patterns and cavitation, may be sensitive to the type of hull form; for example, it may be different for an auxiliary and a surface combatant.

With these three multiplicative factors, the maximum amplitude of the periodic thrust at the thrust bearing is estimated to be 27 times the periodic thrust amplitude calculated at the thrust bearing using propeller unsteady lifting surface theory and shafting response formulations for shaft amplification.

These factors are intended to be sufficiently conservative to ensure that the requirements of MIL-STD-167 are met for all operating conditions (and likely statistical variations over the lives of the ships of the class) yet not so conservative that they unnecessarily control the design of the propeller or propulsion system. Measurements on the AO 177 and AO 178 suggest that these factors are reasonable for this application; however, it is difficult to define precisely the individual factors due to variations with operating conditions, time, and between different ships of the class, and because the measurements are made on the shaft some distance from the propeller. The distance between the point of measurement on the shaft and the propeller makes it very difficult to separate amplifications in the propulsion system from increase in propeller periodic thrust. This is especially critical between 90 percent of full speed and full speed on the AO 177 Class because of the probability of longitudinal shaft resonance at approximately 10 rpm above full power.

Perhaps the most conservative part of the analysis lies in the assumption that the three factors of 3 are multiplicative to give a worst case factor of 27. There may be some nonlinear effects between the three factors so that the maximum factor is less than 27. As stated previously, one of the criteria is to avoid thrust reversal of the main thrust bearing. Thrust reversal of the AO 177 bearing did not occur under any trial conditions; however, the thrust was not measured at the bearing. The maximum periodic thrust at the bearing, based on measurements on the main propulsion shafting and calculated amplification of the propulsion system between the measured point and the bearing, is 25 percent of the time average thrust at full power steady ahead operation. This represents an estimated factor of safety of four.

These amplification factors result in the requirement that the calculated blade frequency thrust amplitude at the propeller must be less than 1 percent of the time average thrust, which is a severe requirement. It is common commercial ship practice to allow blade frequency thrust to be 8 percent of the time average thrust, and in some cases as high as 12 percent.[6]

[6] Private communications with staff of DnV.

The more restrictive upper limit on the AO 177 Class is due, in part, to the requirement that it be able to execute full rudder turns at any speed, and to the higher maximum speed than is typical of commercial ship practice.

Consideration of powering, cavitation, clearances, and strength dictated the following:

Diameter D, m = 6.4 to 7.3
Expanded area ratio A_E/A_0 = 0.77

Therefore, calculations of the six components of bearing forces and moments were made for A_E/A_0 = 0.77, for diameters just indicated, for five and seven blades, and a range of skew distributions. These calculations were made using the unsteady lifting surface procedure of Tsakonas et al [8], which does not consider the influence of cavitation. These calculations were based on the pertinent harmonics of the model nominal wake at full power steady ahead operation in a calm sea without corrections for the influence of Reynolds number, the effect of the propeller on the wake (effective wake), or possible temporal variations in the wake. The limitations concerning the lack of consideration of cavitation and the use of time average nominal model wake are fully appreciated; however, validated procedures for quantitatively calculating the influences of these effects were not (and are not) available. Nevertheless, as mentioned previously, the influences of these effects was considered empirically in calculating the allowable limits of 13.3 kN (3000 lb) for the blade frequency thrust and 8.9 kN (2000 lb) for blade frequency vertical and transverse horizontal force components.

These calculations indicated that in order to meet concurrently the following two requirements:

1. produce blade frequency thrust that is less than 13.3 kN (3000 lb), and
2. have a blade planform with neither a significantly concave trailing edge nor a pointed trailing edge near the tip,

it is necessary to have a seven bladed propeller with 6.4 m diameter (21 ft), nonlinear distribution of skew with approximately 45 deg skew near the tip, and relatively short chords at the outer radii. Concave and pointed trailing edge planforms were judged to be undesirable from considerations of strength and damage susceptibility, especially during astern rotation. The diameter had a first order influence on these calculations because the axial components of the fifth and seventh harmonics of the wake have a reversal of sign at radii less than 6.4 m (21 ft) as will be seen in the wake harmonics distributions. In order to reduce the blade frequency thrust to less than 13.3 kN (3000 lb) with five blades would necessitate substantially larger maximum skew angle than with seven blades due to the combination of longer wavelength and larger amplitude of the fifth harmonic of the wake than of the seventh harmonic of the wake. The combination of higher skew and wider chords for a five bladed propeller would result in a blade profile with unacceptably pointed trailing edge near the tip. Therefore, a five bladed propeller was unacceptable. The final skew distribution was carefully selected to obtain the most effective cancellation of periodic propeller loading over the propeller radius so that the specified bearing force criteria were met.

These calculated values, together with values calculated in 1981 by Det norske Veritas [9] using an unsteady lifting surface procedure based on a vortex lattice approach without cavitation but with an approximate correction for effective wake based on the method of Huang and Groves [10] for a body of revolution, are given in Table 4. The values calculated by Det norske Veritas are greater than the specified limits.

The net inaccuracies in these predictions are judged to be 26.7 kN (6000 lb) or 200 percent of the limit on blade frequency thrust and 300 percent of the limit on blade frequency

Table 4 Bearing force components for AO-177 propeller

	Specified Upper Limit		Tsakonas et al [8], Model Nominal Wake		Det norske Veritas [9], Estimated Model Effective Wake	
	kN	lb	kN	lb	kN	lb
$(F_x)_7$	13.3	3000	11.6	2600	18.7	4200
$(F_y)_7$	8.9	2000	4.45	1000	25.4	5700
$(F_z)_7$	8.9	2000	0.89	200	25.4	5700

transverse force components, based on the cumulative effects of inaccuracies and omissions in the analytical computational methods, and errors due to wake measurements and scaling effects. These inaccuracies are, in part, compensated for by the empirical factors incorporated in the specified limits, especially the factor of 3 for the estimated increase in $(F_x)_n/T$ between 90 percent and 100 percent of full speed, and the factor of 3 for the amplitude modulation, as discussed previously. Although these calculated results are estimated to be inaccurate relative to the small periodic propeller shaft excitation forces being calculated on the highly skewed propellers, it is believed that these calculated results give a realistic indication of the influence of propeller design parameters on the periodic propeller shaft excitation forces. Further, the methods used in the propeller design for the AO-177 Class represent the then-current state of the art for calculating these forces.

Direct measurements of the propeller shaft excitation forces were not made on the AO-177 Class, however, as discussed previously, measurements of the periodic longitudinal response were made on the shafting at some distance from the propeller. From these longitudinal shaft response measurements and a mathematical model of the shafting system, the blade rate propeller thrust is calculated to be between 0 and 26.7 kN (0 and 6000 lb); that is $0 \le (F_x)_7/T \le 0.02$. This agrees reasonably well with the values predicted in the propeller design process. The blade rate thrust cannot be determined more accurately from these full-scale measurements due to measured variations with operating conditions, time, and between different ships of the class, and inaccuracies in calculating amplifications in the propulsion system including possible resonances.

It was realized that propeller-induced hull forces due to transient cavitation could produce hull vibration and airborne noise. However, no reliable procedure for quantifying these effects existed. Had such a procedure existed, it would have been applied and, it is hoped, a balance would have been struck between machinery vibration and hull noise and vibration performance. In the absence of such knowledge and procedures, the machinery vibration criteria, for which design procedures did exist, drove the design. The blade tips were unloaded relative to the Lerbs optimum criterion in some attempt to reduce the periodic hull forces; however, the effectiveness of this unloading is unclear for a propeller operating in a severe wake and with transient cavitation as is the case for the AO-177. Further, it was judged that the blade skew would dramatically reduce propeller-induced hull forces relative to those induced by the corresponding propeller without skew [11, 12, 13]. Some semi-empirical criteria existed for judging the likelihood of propeller erosion and propeller-induced hull vibration; however, these are not applicable to the present design since its geometry is outside the range of the data base on which these semi-empirical methods are based. In particular, this design has narrow blades near the tip, seven blades, and high skew which are not considered in the semi-empirical criteria.

Fig. 3 Seven-bladed skewed propeller on the AO-177 (note installation of wake-improving fin)

The final pitch and camber were determined by the lifting-surface procedure of Cheng [14] with thickness corrections by the method of Kerwin and Leopold [15]. Table 2 gives the pertinent details of the final configuration. Figure 3 shows photographs of the propeller installed on the ship.

The problems

During builder's sea trials, the AO-177 exhibited several unsatisfactory symptoms at and near full-power operation:

- High inboard airborne noise levels in many spaces in the stern region of the ship, and up into some deckhouse spaces as well
- Incubation zone erosion damage to the propeller (burnishing and dimpling) and bent trailing edge
- Heavy localized vibrations, particularly in the areas directly over the propeller

Airborne noise

Extensive airborne noise measurements made during the builder's trials indicated some high levels that exceeded criteria

Table 5 Criteria noise levels—permissible airborne sound pressure levels (in dB relative to 20 μPa)

Type of Space	Octave Band Center Frequency, Hz									
	32	63	125	250	500	1000	2000	4000	8000	SIL
Large command and control	90	84	79	76	SIL	SIL	SIL	69	68	74
Small command and control, and administrative spaces	90	84	79	76	SIL	SIL	SIL	69	68	64
Living spaces	90	84	79	76	75	71	70	69	68	X
Medical	85	78	72	68	65	62	60	58	57	X
Shops, service spaces, passages and topside stations	105	100	95	90	SIL	SIL	SIL	85	85	[illegible]
Machinery	105	100	95	90	90	85	85	84	83	X

Speech interference levels (SIL). In the octave bands where SIL values apply, the noise levels may exceed the SIL value in any of the three SIL octave bands provided the arithmetic average of the levels in the SIL octave bands do not exceed the specified SIL value.

given in the shipbuilding specification. Excessive noise levels in berthing, lounge, recreation, mess, and shop spaces aft of Frame 94 were identified consistently as being caused by the propeller excitation. *In all, 23 compartments were reported* to have unsatisfactory noise levels associated with the propeller. Locations of the troublesome spaces within the ship are indicated by the cross hatched areas in the aft-end inboard profile of Fig. 2. The noise level criteria for Navy ships depend on the *compartment* usage. The allowable sound levels applicable to the AO-177 are given in Table 5.

As an illustration of the character of the problem, Fig. 4 shows octave band sound pressure levels measured during the initial AO-177 builder's trials in four representative compartments: Crew Berthing and Dressing Nos. 4, 5, and 6, and the Gym. All these spaces have the same noise criteria. These data were measured using the approach described in Appendix 1. As indicated in Fig. 4, low *frequency noise levels in all compart*ments were 5 to 15 dB above the criteria and high-frequency levels ranged from 5 dB above to 6 dB below the criteria. Similar conditions were found for most of the spaces identified as having noise problems, each with respect to the pertinent criteria levels for the space. Another space near the top of the deckhouse also experienced marginally unsatisfactory propeller-associated noise, but only at the lowest octave band, and it was discernible as a low rumbling sound.

Vibration amplitudes representative of the hull girder response were measured at several locations on main structural girders on the ship centerline in the steering gear compartment, engine room, and at the top of the stack of deckhouses. These were all found to be of satisfactory magnitude according to [illegible] and also were judged to be acceptable from the point of view of recent ISO recommendations [16]. Hence, although there was clearly excessive propeller excitation with this ship, it was manifested principally as unsatisfactory airborne noise levels, and not as unacceptable hull girder vibration.

Propeller damage

A week after the builder's trials, the propeller was visually inspected by ballasting the ship down by bow to expose the upper third of the propeller. A blade-by-blade check revealed that damage had occurred on the suction (back) side of all blades, with *most of the distress centered between the 0.8R and 0.9R radii*. The damage consisted of a roughly semicircular patch of initial-stage cavitation erosion along the trailing edge of each blade about 20.3 cm (8 in.) in maximum width *and a* rolled portion of the trailing edge bent from the suction side toward *the pressure side*, about 30 cm (1 ft) long with a lip on the pressure side of maximum height 3 to 6 mm ($\frac{1}{8}$ to $\frac{1}{4}$ in.). A smaller, lightly dimpled patch was centered near each blade tip along the *trailing edge*, see Fig. 5. No distress was found on the pressure side.

Propeller cavitation

Propeller viewing and photography were performed on the AO-177 using a periscope projecting through the hull which provided a reasonably wide field of view. Photographs of the propeller were taken for a range of blade angular positions *during daylight hours using ambient light*[7]. *Only a description* of the visual observations is presented here for the full load, full-power condition. Photographs and sketches of the cavitation are presented later.

[7] More details are presented in a report of restricted distribution by J. Kelley and S. D. Jessup entitled "Results of Propeller Vibration Cavitation Investigation on USS *Cimarron* (AO-177) During Acceptance Trials," May 1981.

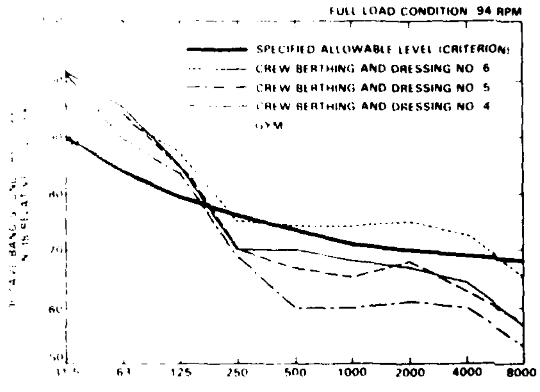


Fig. 4 Example excessive airborne noise levels measured during builder's trials

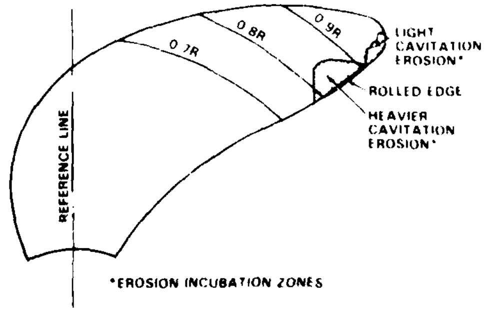


Fig. 5 Sketch of cavitation damage after builder's trials

Clouds of cavitation were observed on the suction side of the blades from the 0.7*R* to the tip. Violent clouds of cavitation formed as each blade tip passed through the top position of rotation. Each cloud formation was then shed downstream along the starboard side of the rudder. Such formation of suction side cloud cavitation is generally associated with vigorous cavity collapse. In this case, cavitation erosion damage would be expected to occur at the suction side trailing edge near the blade tip as discussed by van Manen [17] and Lindgren and Bjarne [18]. A sharp banging sound occurred at blade passing frequency and is believed to correspond to the violent collapse of the cavitation.

Investigations and design modification

Scope

The pursuit of a successful design modification for the AO-177 was guided primarily by the results of model experiments. These were aimed at several specific objectives:

- Verify the cause of the problems.
- Formulate and develop possible solutions and obtain evaluations of them.
- Determine the most expedient correction scheme, and explore the consequence of its implementation.

At the outset, the most probable source of the problems was thought to be hydrodynamic excitation caused by intermittent cavitation on the propeller blades passing through severe velocity excursions associated with the main wake shadow. That is, airborne noise is generated by structureborne localized vibrations caused by fluctuating hull surface pressure excitation arising from the periodically collapsing blade sheet cavities. Propeller blade erosion and bent trailing edges are common symptoms of cloud cavitation that occur when blade sheet cavities collapse with sufficient violence and proximity to the blade surface [17-19].

The mechanism producing large pressure pulse excitation and attendant propeller damage involves a complicated interaction of the cavitating flow over propeller blades with rapidly changing velocities associated with wake patterns having severe nonuniformity. Some of the important details of this interaction are described, for example, by Huse [20], and in many subsequent studies. During the past decade, there has been a tremendous growth of literature centered on surface pressure excitation and resulting ship vibration and noise problems. References [21] and [22], for instance, are representative of collections of published efforts devoted to these topics. It is generally known that steep and narrow main hull wake characteristics can give rise to excitation problems [23, 24], and that details of propeller blade planform and section geometry can also markedly influence the excitation levels. The difficult question to answer is whether some particular wake together with a given propeller configuration will cause problems at a given speed. For the evaluation of the AO-177, this question was addressed experimentally. As will be shown, there is a strong case for attributing the problems of the AO-177 to the effects of unsteady growth and collapse of sheet cavitation.

Possible solutions involve changing the wake velocity distribution, altering the propeller design, or both. The several means of modifying the wake distribution include: bulbous stern designs [2, 25] to help create more rounded wake contours (to reduce spike-like features) and produce a more uniform circumferential velocity variation, flow-improving fins [1, 2, 26-29] to guide more flow into the upper propeller disk region by increasing local axial flow speed, upstream propeller ducts [29, 30] to help induce a more stable and uniform through-flow to the propeller, and various types of wake spoilers or flow deflectors [31, 32] to induce flow changes selectively just forward of the propeller location. A bulbous stern was not pursued as a corrective measure since the structural changes to the ship would have been much too radical and expensive. Flow deflectors such as those noted by Rutherford [25] were not pursued.

It was decided to investigate flow-improving fins, an upstream duct, and propeller design changes as the options for reducing the excitation levels on the AO-177.

Two basic fin designs were selected for model evaluation: a tunnel-type configuration modeled after a fin described by Rutherford [25] that was successful in helping to relieve excessive vibrations on a moderate-block-coefficient refrigerated pallet cargo ship, and a flow-accelerating configuration suggested by SSPA. Line drawings of these fin designs are shown in Figs. 6 and 7. Aside from the differences in shape and size, the tunnel-type fin features a tip clearance ratio of $a_z/D = 0.12$, while the flow-accelerating fin has $a_z/D = 0.10$. The detailed design of the tunnel fin design for the AO-177 application was carried out by Hydronautics, Inc.

Experiments were conducted at both DTNSRDC and SSPA with scale models of the AO-177 hull of identical size. This made it possible to use the same model propeller (DTNSRDC Model 4677) for tests involving flow visualization, pressure pulse amplitudes, and powering. Table 6 summarizes the basic dimensions and conditions of the models.

Model flow visualization and wake studies

In order to gain preliminary understanding of the effect of a fin on the quality of wake flow near and approaching the propeller aperture, flow visualization experiments were performed in the Circulating Water Channel at DTNSRDC with the propelled AO-177 model, at the appropriate scaled propeller rpm and at the Froude-scaled speed corresponding to 20 knots full scale [33]. Both full load and ballast conditions were simulated. Yarn tufts were attached from Station 17 aft, and to the rudder.

From observations of unstable or reversing tuft patterns it was possible to detect regions of very slow or separated flows. In the case of the AO-177 with no fin, and with the as-built propeller design, the flow along a narrow strip near the centerline of the upper aperture was found to show some variable or near-separated flow behavior in both the load and ballast conditions. It was also found that the tunnel-fin produced a noticeably less variable flow behavior in the vicinity of the propeller plane, compared with the flow with no fin. The sketch of Fig. 8 shows the superposed tuft patterns taken from photographs of the port side aft of the model in the channel, indicating the hull flows both without and with the tunnel-fin. From this comparison, the discernible effect of the installed fin seemed to be concentrated near the partial tunnel underside where several tufts (and streamlines) were deflected slightly downward from their original orientation. This corresponds to more of the buttock-aligned flow being directed into the propeller disk region.

Wake surveys were conducted at DTNSRDC with the AO-177 model operated with and without the fin configurations, in both the full load and ballast conditions [34]. These experiments were performed with a wake rake consisting of five 5-hole spherically headed pitot tubes rotated systematically around the complete propeller disk. For the full-load displacement condition, the measured circumferential distributions of the three velocity component ratios of the nominal wake at radius ratios $r/R = 0.359, 0.556, 0.775, 1.017$, and 1.178 are shown in Figs. 9 through 13, respectively. The cases included are the AO-177 hull with no fin, with the tunnel-fin, and with the flow-accelerating fin. These plots are arranged to show the effect of the main wake shadow in the center of each graph. It

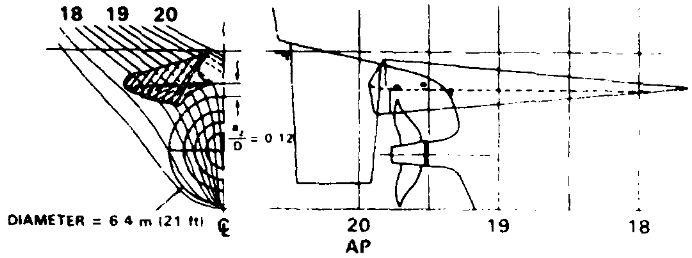


Fig. 6 Tunnel-fin configuraiton

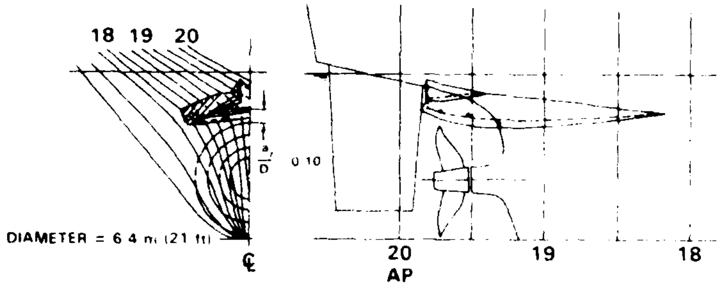


Fig. 7 Flow-accelerating fin configuration

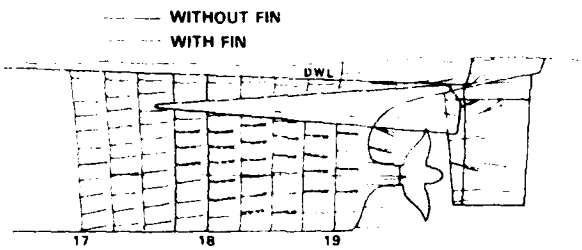


Fig. 8 Model tuft patterns with and without tunnel-fin

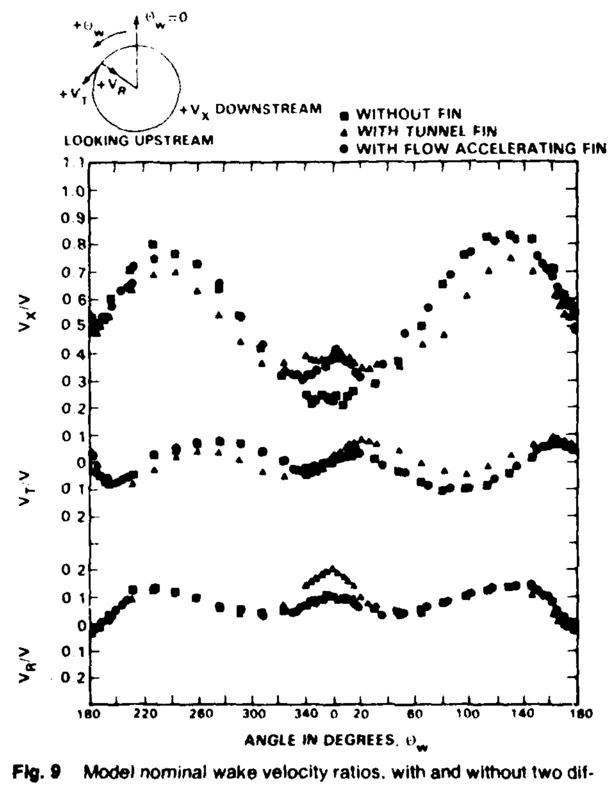


Fig. 9 Model nominal wake velocity ratios, with and without two different fins, at radius ratio $r/R = 0.359$

Table 6 Model hull and propeller geometry of AO-177 (scale ratio $\lambda = 25.682$)

Hull	
length	$L_{PP} = 6.527$ m (21.42 ft)
length on waterline	$L_{WL} = 6.653$ m (21.83 ft)
beam	$B = 1.044$ m (3.43 ft)
draft (mean) full load	$T_m = 0.374$ m (1.227 ft)
material:	wood for experiments at DTNSRDC; paraffin wax for water tunnel experiments at SSPA
turbulence stimulation	none on DTNSRDC model; 1-mm trip wire at 0.05 L_{WL} on model at SSPA
Propeller	
diameter	$D = 24.92$ cm (9.812 in.)
pitch-to-diameter ratio	$(P/D)_{0.7R} = 1.25$
number of blades	$Z = 7$

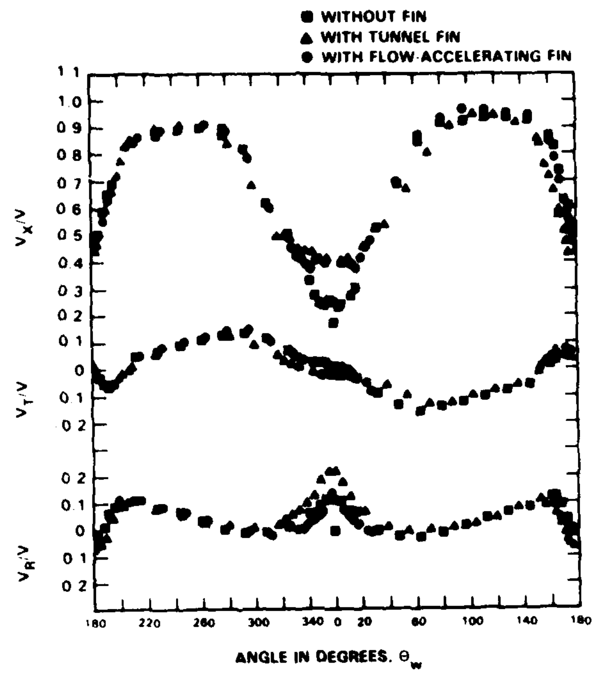


Fig. 10 Model nominal wake velocity ratios, with and without two different fins, at radius ratio $r/R = 0.556$

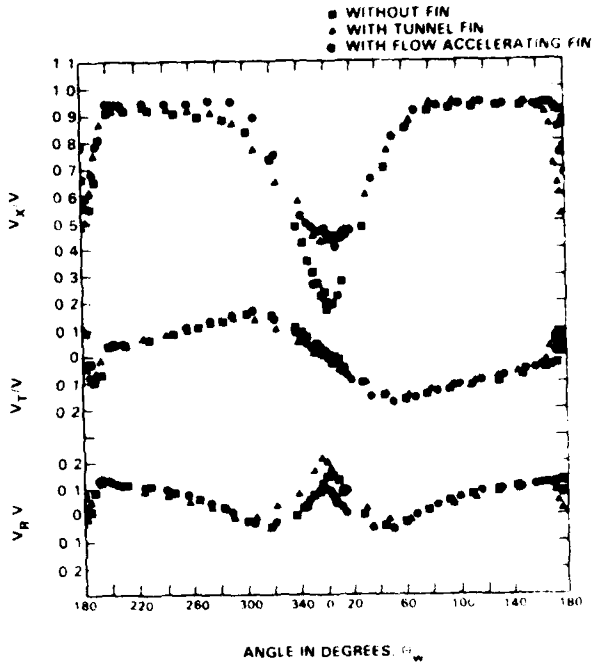


Fig. 11 Model nominal wake velocity ratios, with and without two different fins, at radius ratio $r/R = 0.775$

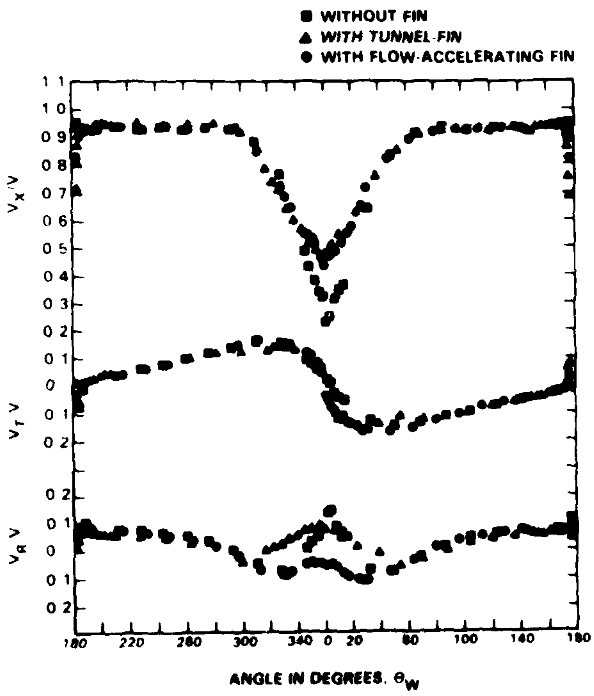


Fig. 12 Model nominal wake velocity ratios, with and without two different fins, at radius ratio $r/R = 1.017$

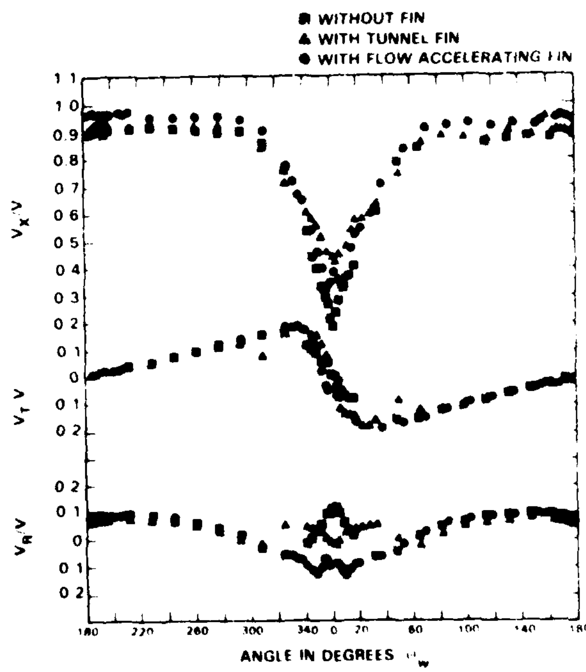


Fig. 13 Model nominal wake velocity ratios, with and without two different fins, at radius ratio $r/R = 1.178$

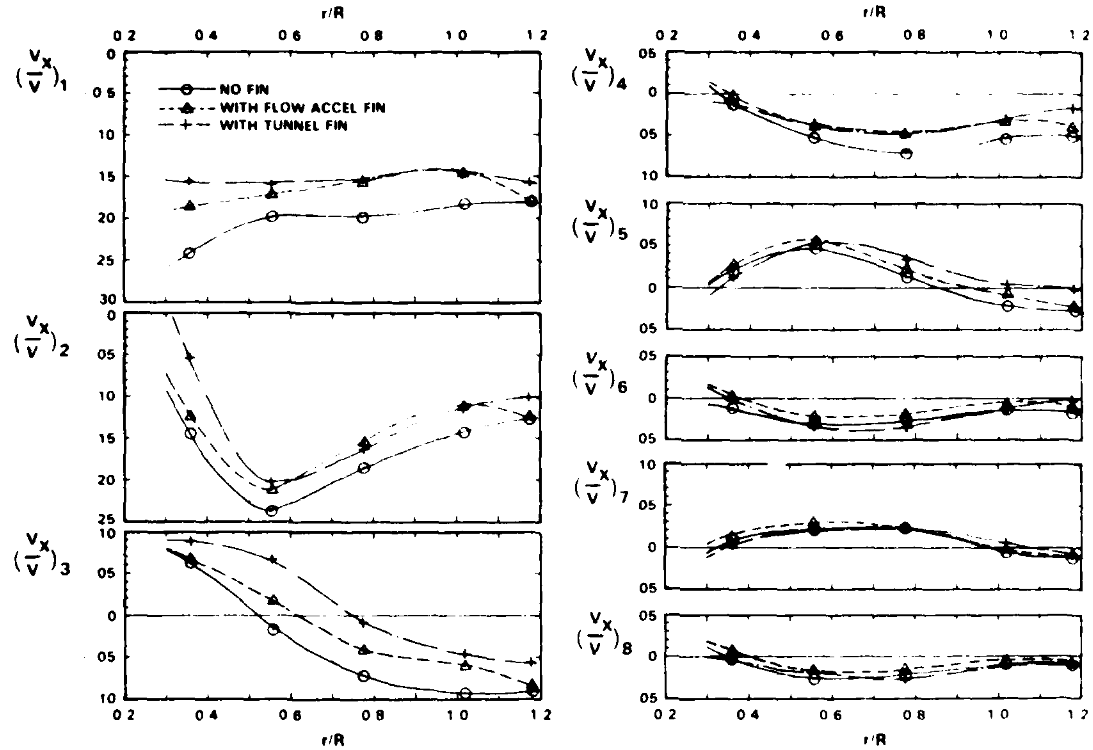


Fig. 14 Comparison of radial distributions of axial component of wake harmonics, with and without the two different fins

is noted that for each of the two with-fin velocity patterns there is an increase of the axial velocity component V_X/V (decrease of wake peak) that occurs locally within the angular interval 40 deg to either side of the 12 o'clock position. The distributions of the axial velocity components due to the two different fin configurations seem to differ little in magnitude and detail. There are, however, noticeable differences in the distributions of the tangential and radial component ratios V_T/V and V_R/V for the different fin types.

Radial distributions of the harmonic amplitudes $(\tilde{V}_X/V)_n$ of the longitudinal velocity component for harmonics $n = 1$ through 8 are shown in Fig. 14 comparing the full load displacement cases of the hull with no fin, with the tunnel-fin, and *with the flow-accelerating fin*. For the lowest harmonics, $n = 1$ and 2, the amplitudes are systematically reduced by the action of each of the two fin configurations. For the higher harmonics, the effects of the two fin systems become mixed and apparently subject to no simple or generalized trends. It is known from previous investigations and extensive comparative work (see, for example, Hylarides [3]) that the reductions of the lowest harmonic orders of the V_X/V velocity field can produce measurable reductions in the levels of propeller excitation due to intermittent blade cavitation. Both fin configurations under consideration were found to produce improvements in the flow to the propeller in the upper disk region (near 12 o'clock) and both fin wakes showed reduced magnitudes in the first two harmonics.

Table 7 **Conditions for original configuration experiments**

Condition	Ship Speed V (knots)	Ship Scale rpm	J	Number Cavitation σ
Full load	21.6	98.3	0.77	4.7
Ballast	23.2	100.3	0.81	3.5

Propeller-excitation model experiments

Cavitation tunnel experiments were carried out in the Swedish Maritime Research Centre (SSPA) Tunnel No. 2 with the DTNSRDC model propeller of the AO-177 operated behind a complete wax model of the AO-177 hull. These experiments included measurement of propeller thrust and torque, systematic observations of the propeller cavitation patterns, checks on cavitation erosion tendency, and measurements of the propeller-induced pressure pulse amplitudes at several points on the hull surface. These experiments provided a crucial body of evidence that verified that propeller blade intermittent cavitation was the likely cause of the excitation and initial-stage erosion problems of the AO-177, and supplied the technical basis for choosing a design correction for the ship from among the several proposed options. The results of all these experiments are recorded in references [35–37].

Original AO-177 configuration. Initial experiments were run with the design propeller operating behind the unaltered AO-177 hull at the conditions given in Table 7. Observations of the propeller blade cavitation patterns at the simulated conditions of both full-load and ballast displacements indicated that extensive sheet cavitation appeared on the outer radii of

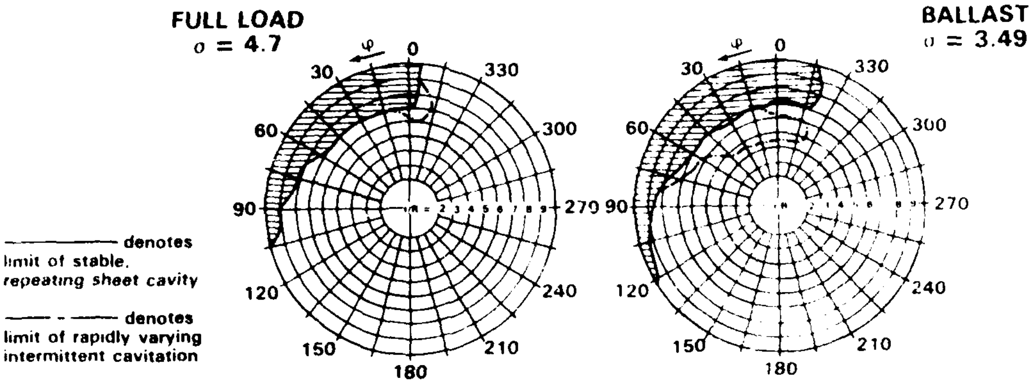


Fig. 15 Cavitation extent diagrams for unmodified AO-177 at full load and ballast conditions [position angle φ measured counterclockwise looking aft (downstream)]

each blade from about 0.6*R* to the tip as it passed through the main wake field. Figure 15 indicates the radial and circumferential extent of the blade cavitation during one revolution for the two displacement conditions. Cloud cavitation produced by the unstable breakup of the sheet cavities formed in patches downstream and overlapping the blade trailing edges around the 0.8*R* to 0.9*R* radii. SSPA's standard erosion tendency test using a coating on the blade surface predicted blade surface erosion around the 0.85*R* radius at the trailing edge.

The pressure pulse magnitudes at various locations around the propeller aperture were found to be rather high as shown in the longitudinal distributions of blade rate pressure double amplitudes plotted in Fig. 16. Two representations of the same pressure pulse signature are displayed: the oscilloscope-recorded value of maximum peak-to-peak at blade rate, and the mean of the highest 5 percent double amplitudes at blade rate as determined from Fourier analysis. The positive phase angle Φ here indicates the angular delay of the suction peak occurring after the blade reference line has passed the upright position. The longitudinal distribution of the phase angle is nearly constant, a typical attribute of the fluctuating pressure field from cavity volume variations.

For the point on the hull centerline directly over the propeller tip, the variations of blade rate pressure double amplitudes with ship speed are shown in Fig. 17 for both full load and ballast conditions. The measured noncavitating pressure pulse double

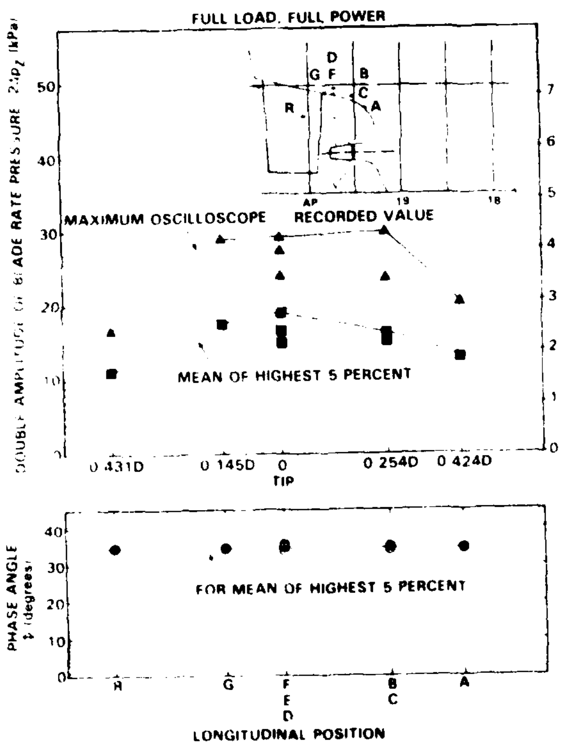


Fig. 16 Longitudinal distribution of blade rate pressure pulse double amplitude and phase angle for unmodified AO-177

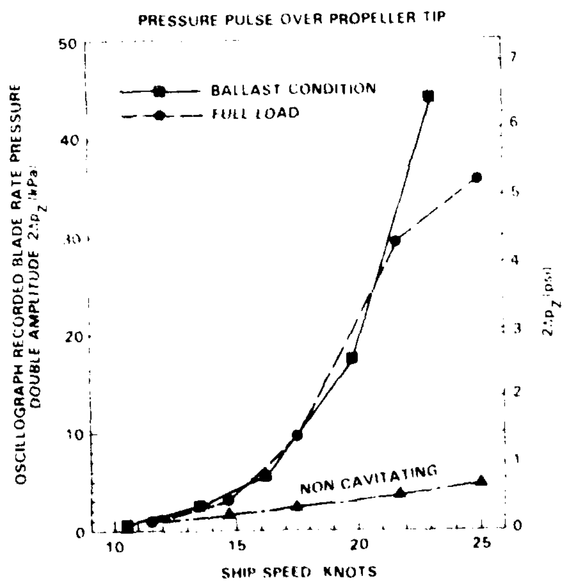


Fig. 17 Variation of blade rate peak-to-peak hull pressure over propeller tip versus ship speed

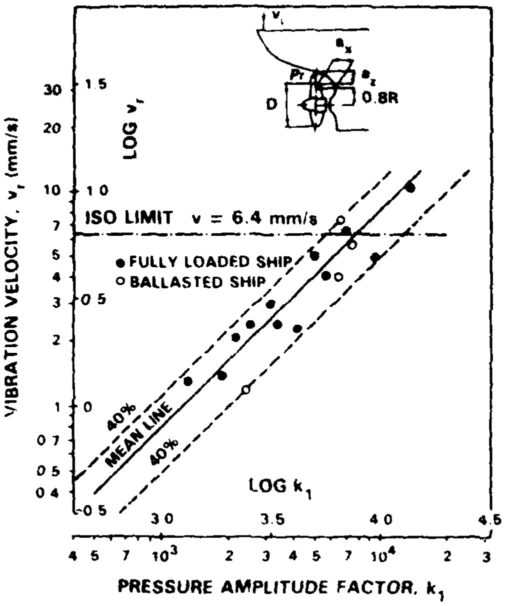


Fig. 18 SSPA pressure pulse-vibration response criterion (from reference [27])

amplitudes are also presented in Fig. 17. This latter comparison shows an order-of-magnitude increase in the pressure pulses due to blade cavitation in the high speed range. This effect, the slow longitudinal diminution of the pressure amplitudes forward and aft of the propeller plane (Fig. 16), and the almost constant longitudinal distribution of pressure pulse phase angle (Fig. 16), are typical characteristics of the excitation produced by blade cavity volume variations.

Simple criteria are available for judging whether the scaled-up fluctuating pressure amplitudes are excessive from the point of view of propeller-excited hull vibrations. Typically, these prescriptions are based on correlations between hull girder vibration levels that exceed the limits recommended by the ISO or by the pertinent authority for the ship type involved. Unfortunately, there are no known elementary criteria that pertain specifically to airborne noise in this same fashion. It has been indicated, for example, by Ward and Willshare [38] that excessive airborne noise often accompanies the problem of severe aft-end vibrations, and is generally attributable to the same unsteady cavitating-propeller excitation. It is useful, for a frame of reference, to consider the present problem in terms of criteria for hull girder vibration, which deal with the lowest end of the pressure pulse excitation spectrum. The simplest criteria are the recommended single-point, single-value limits for hull pressure pulses directly over the propeller tip. The typical limiting values of blade rate double amplitude discussed in reference [39] are in the range $2(\Delta P_Z)_{\text{allowable}} = 15$ to 20 kPa (2.25 to 3 psi). Since the corresponding model test value for the AO-177 was found to be about 29 kPa (4.35 psi), this seemed to verify the presence of an excessive excitation.

The criterion developed by SSPA [27] and embodied in Fig. 18 is based on a correlation of pressure pulse amplitude and hull vibration velocity response v_r at the fantail centerline. It provides for determining limiting values of pressure amplitudes that depend roughly upon the relative size of the ship and upon the tip clearances a_z and a_x, as specified in the dimensional pressure factor

$$k_1 = 2(\Delta P_Z)\frac{10^3 D^2}{\nabla}\frac{a_z}{a_x}$$

where

$2(\Delta P_Z)$ = blade rate pressure pulse double amplitude (Pa)
D = propeller diameter (m)
∇ = volume of displacement (m³)
a_z = vertical tip clearance
a_x = horizontal blade clearance measured from midchord at 0.8R radius forward to hull

This criterion was developed from data on ships having propellers with fewer than seven blades. For the unaltered AO-177, using the mean-line value for the ISO limit on vibration velocity of 6.4 mm/s (252 mils/s), the allowable blade rate pressure fluctuation over the tips according to the SSPA criterion is $2(\Delta P_Z)_{\text{allowable}} = 9.7$ kPa (1.41 psi). This is smaller than the range of values allowed by the single-point, single-value recommendations.

In any case, the propeller-excitation levels inferred from the model tests of the AO-177 are excessive, and indicate that troublesome hull vibration might be expected. As noted at the outset, the problems with the AO-177 did not appear in the form of large hull girder vibrations, either at the fantail centerline, or at the top levels of the deckhouse, but rather showed up as high-level, low-frequency inboard *airborne noise, transmitted by localized structureborne vibrations*. It would appear that this indicates either a model scaling-correlation difficulty with the SSPA criterion, perhaps because the AO-177 propeller has seven blades, or that there are unusual characteristics of the AO-177 structural impedance properties for girder vibrations and airborne noise. This may also be related to the excitation frequency ranges associated with the seven-bladed propeller being somewhat higher than is common practice for ships of this type.

Experiments with alternative (stock) propellers. Measurements of propeller-induced hull pressures and observations of cavitation patterns were made for three stock propellers on the AO-177 model hull without fins in the SSPA water tunnel. The objective of these experiments was to obtain data on the influence of specific propeller parameters on the cavitation patterns, tendency towards erosion, and propeller-induced hull pressures. This information was necessary for

1. evaluating the relative potential gains to be achieved by redesigning the propeller and by modifying the hull wake, and
2. providing guidance for a propeller redesign in the event that this option was selected.

The schedule did not permit propeller models to be designed and built specifically for these experiments; therefore, the most suitable stock propellers were selected.

The existing (stock) propeller models were chosen in an attempt to represent the following geometries:

A. A five-bladed, 21-ft-diameter (6.4 m) (full-scale) skewed propeller with wide blades near the tip, and a large skew gradient near the tip. It was speculated that a design with these general characteristics would be the most promising alternative design for reasons described in the section on propeller redesign.

B. A four-bladed, 21-ft diameter (6.4 m) propeller, preferably with a skew distribution similar to that for the selected five-bladed propeller. This would help isolate the influence of number of blades.

C. A seven-bladed 23-ft-diameter (7.0 m) propeller. This

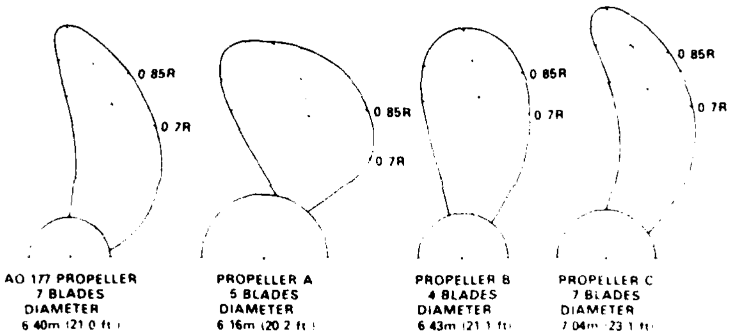


Fig. 19 Propellers evaluated in AO-177 experiments at SSPA

propeller was selected in an attempt to isolate the influence of diameter

These target geometries for the alternative propeller were selected as representing the most effective candidates for providing information for improving the erosion and airborne noise on the AO-177 It was desired that all the propeller models have values of other geometric parameters which are consistent with the requirements of the AO-177, especially expanded area ratio average pitch, and radial distributions of pitch skew, thickness and camber

These requirements could be met only partially with existing model propellers, however, in most cases the geometries were sufficiently near the desired values for the objective of these experiments The selected propeller models are compared in Fig 19 The best available four-bladed stock propeller had neither high skew nor a suitable expanded area ratio, however, it was experimentally evaluated in an attempt to obtain some additional information on the influence of the number of blades

Experiments were conducted at the estimated full-power, [illegible] point with each propeller, corresponding to the con[illegible] given in Table 8

The cavitation results showed that all of the propellers had cloud cavitation near the trailing edge except Propeller A For Propeller A, the back sheet cavitation remained as a clear stable sheet that merged with the tip vortex and collapsed substantially downstream of the propeller The resulting collapse of the sheet cavitation on this propeller appeared to be much less violent than on the other propellers This type of behavior should be beneficial for reducing both the tendency towards erosion and periodic hull pressure amplitudes Figure 20 compares the patterns on the model of the AO-177 propeller with Propeller A

The hypothesized mechanism which drives the sheet cavitation on Propeller A to merge with the tip vortex is discussed in the section on the proposed redesign propeller, however, the controlling propeller parameters are thought to be the sweep angle of the leading edge near the tip, and the chord lengths near the tip Propeller A, which is a model of a controllable-pitch propeller, has substantially wider blades near the tip than the AO-177 propeller and Propellers B and C The leading-edge sweep angle near the tip on Propeller A is slightly larger than it is on the AO-177 propeller, and substantially larger than on Propellers B and C

The relative magnitudes of blade rate pressure fluctuations measured on the hull centerline directly over the propellers were found to be as given in Table 9 The reduced pressure pulse amplitude with Propeller A is consistent with the observed less violent collapse of the cavitation on this propeller The

Table 8 Conditions for alternate propeller experiments

Propeller	Ship Speed (knots)	rpm	J	
AO-177	21.6	98	[illegible]	[illegible]
A	[illegible]	[illegible]	[illegible]	[illegible]
B	21.6	98	[illegible]	[illegible]
C	[illegible]	[illegible]	[illegible]	[illegible]

higher pressures with Propeller C are due predominantly to the substantially reduced tip clearance with this propeller

As discussed in the section on the proposed redesign propeller the radial distribution of loading (pitch and camber) near the tip may also have an influence on the violence of the cavitation collapse, and on propeller-induced hull pressures Propellers B and C have significantly less pitch and camber reduction near the tip than either the AO-177 propeller or Propeller A (see Fig 21) However, the influences of radial distribution of loading near the tip on the violence of the cavitation collapse and propeller-induced hull pressures could not be isolated from these data because more than one propeller parameter was changed simultaneously

In conclusion, these experiments suggest that if a propeller redesign is to be undertaken desirable characteristics are wide blades near the tip with a highly swept leading edge near the tip

Experiments with wake improving appendages Experiments were conducted at SSPA with three sets of stern appendages to explore the possibility of modifying and obtaining a sufficiently improved wake so that the propeller would not have to be changed In addition to the flow-accelerating fin and the tunnel-type fin designs described earlier a retrofit upstream duct concept modeled after a configuration discussed by Takekuma (30) was also considered Such an upstream duct has been shown to be helpful in the reduction of propeller-excited vibrations for full ship forms but not necessarily for slimmer hull forms like the AO-177 Figure 22 is a profile drawing of the duct fitted on the hull indicating how it was arranged ahead of the propeller This duct features nonconstant chord lengths around its periphery

Observations of the blade cavitation patterns and measurements of induced hull pressures were carried out for each of the cases of the modified hull at the estimated full power condition characterized by data given in Table 10 All these tests were run with the design AO-177 propeller

Blade cavitation patterns corresponding to operation with the two fin designs showed some slight shifts in extent both

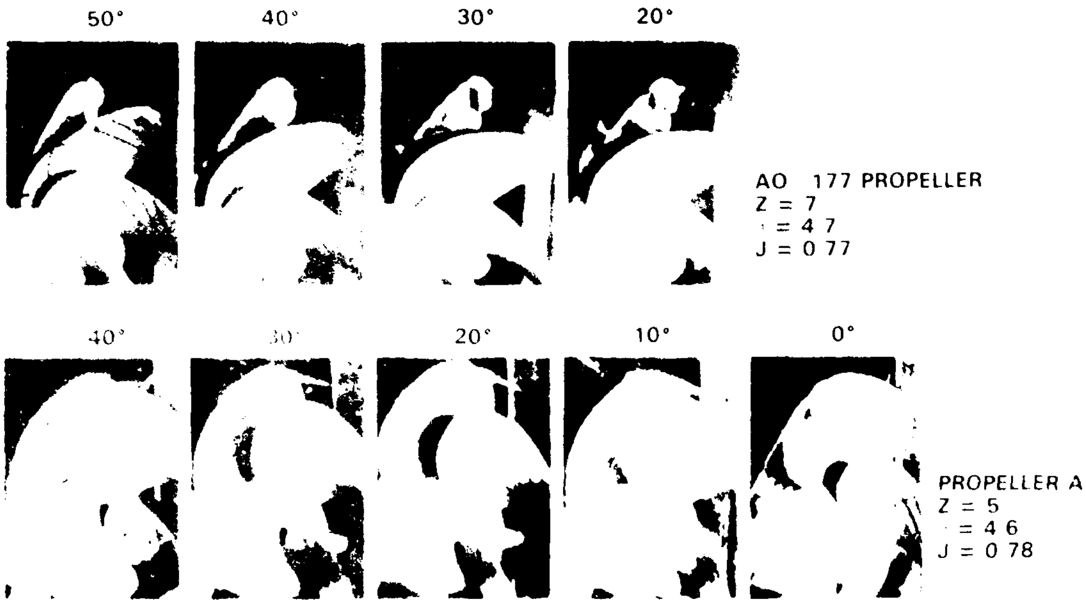


Fig. 20 [illegible] Stock Propeller A behind unmodified hull at simulated full-power, full-load conditions

[illegible] and [illegible]. In these cases the cloud cavitation associated with [illegible] cavities was diminished somewhat [illegible] cavitation with the unappended AO-177 hull [illegible] the duct, the blade cavitation extent in the upper disk was diminished somewhat but a new [illegible] was introduced near the 5 o'clock position [illegible] caused by a local wake peak [illegible] bottom region of the duct. Also with the duct, there was observed a frequent occurrence of tip vortex core cavitation near the 12 o'clock region of the duct exit that had the appearance of lightning strokes leaping from the blade tips to the inside aft end of the duct. Pressure pulses produced by this [illegible] are known to be very large, but since no pressure gages were located within the duct for the AO-177 experiments, the magnitudes of pressure excitation levels on the *inner* duct surface were not determined.

The cavitation sketches collected in Fig. 23 illustrate the changes in gross cavitation extent and cavitation appearance for the simulated full-power, full-load operation of the unmodified hull plus the three modifying appendage configurations. The slight discontinuity in cavitation extent *that* occurs in the blade cavitation pattern for the case of the unmodified

Table 9 Effect of propeller geometry on pressure fluctuations

Propeller	$\Delta P / (\Delta P)_{AO\text{-}177}$
AO-177	1.0
A	0.5
B	1.0
C	1.8

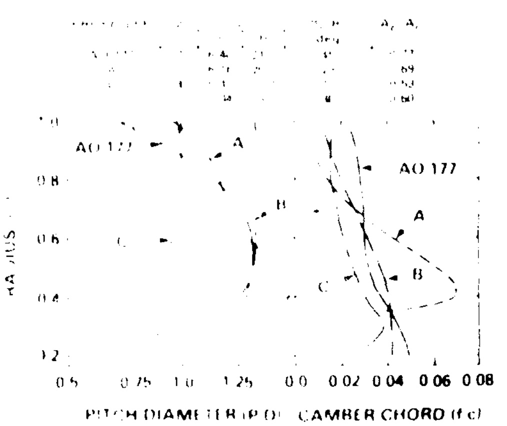


Fig. 21 Comparison of pitch and camber of propellers evaluated in AO-177 experiments at SSPA

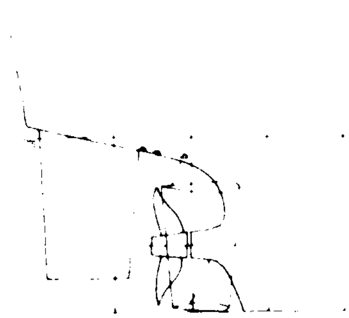


Fig. 22 Retrofit duct configuration

Table 10 Conditions for wake-improving appendage experiments

Modifying Appendage Configuration	Ship Speed V (knots)	rpm	J	
Flow accelerating fin	21.5	[illegible]	0.8[illegible]	[illegible]
Tunnel fin	21.5	[illegible]	0.86	[illegible]
Retrofit duct	21.3	10[illegible]	0.825	[illegible]

hull between position angles of 60 and 70 deg seems to have been smoothed in the sequences recorded for each of the appended hull cases. From visual observations and to some extent from photographs, it appears that for each of the appended hull cases shown, the blade sheet cavity was thinner than that for the case of the unmodified AO-177. There were also noticeable differences in the cavity termination region near the blade trailing edge. In general, for all of the appended hull cases the extent of cloud cavitation was reduced.

Erosion tendency tests were carried out with the AO-177 model propeller with the flow-accelerating fin and with the duct; in both cases, the experiment did not indicate any tendency toward erosion.

Pressure pulse measurements were made at various locations on the *underside of the two fins and on the hull* at positions indicated in Figs. 6, 7, and 22. For the full power, full load conditions appropriate to each configuration, the resulting distributions of blade rate pressure amplitudes are shown in Fig. 24. The resulting distributions of pressure pulse double amplitudes show that the effect of each of the two fin appendages follows a distinctive pattern. Directly over the tip, the pressure pulse levels remain large or may even increase. The tunnel fin, with a vertical tip clearance ratio a_v/D = 0.12, produced a slightly greater pressure pulse level than the unmodified *hull* over the tip but showed much reduced amplitude both forward and aft of the propeller. The flow accelerating fin with a_v/D = 0.10 produced somewhat lower pressure pulse levels over the propeller [illegible] even greater reductions of amplitude compared with the [illegible] forward [illegible] of the propeller plane.

For both Propeller A and the duct appendage, the distributions of pressure pulse amplitudes at points along the hull showed similar reduction, to about 50 percent of the levels of the original AO-177 propeller-hull combination.

There is a subtle correspondence between the appearance of cavitation patterns on the blade profile, as illustrated in Fig. 23, and the details of the resulting pressure pulse excitation shown in Fig. 24. Unfortunately, the important properties of cavity thickness and cavity volume distribution are not indicated in Fig. 23. In fact, these properties are determined experimentally only with great research effort. Therefore the diagrams of Fig. 23 provide only a partial description of the alterations in cavity geometry that are reflected in the changes of pressure pulse levels of Fig. 24.

Figure 24 also shows the allowable pressure double amplitude obtained from the SSPA criterion, Fig. 18, for each of the configurations. The permissible level at the point above the propeller tip for the flow accelerating fin is the highest because [illegible]

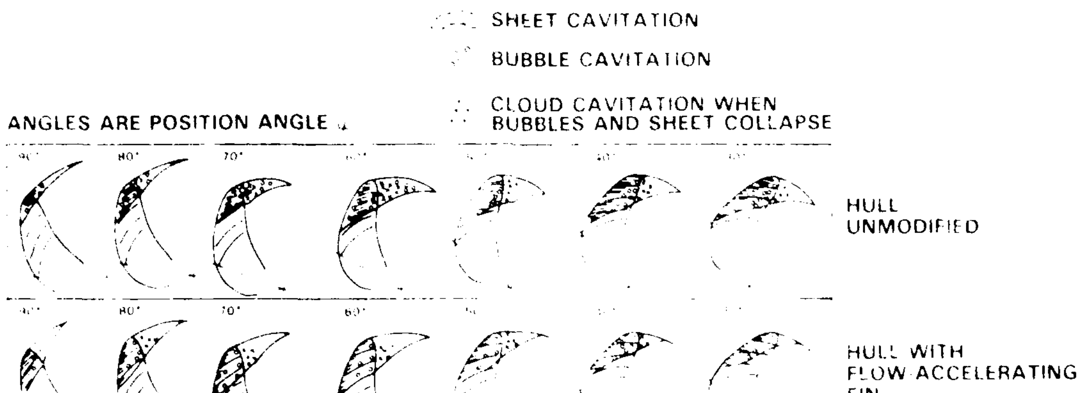


Fig. 23 Cavitation sketches for AO-177 propeller operated with and without various flow modifying appendages (from reference 37)

[illegible]

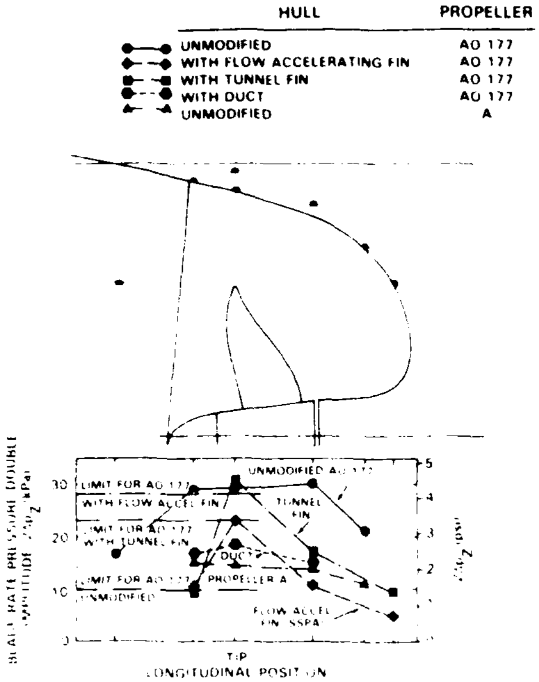


Fig. 24 Comparison of distributions of blade rate pressure double amplitudes for various corrective options for AO-177

tip clearance ratio a_t/D is the smallest of all the arrangements indicated. If it is assumed that the SSPA vibration criterion has somehow the general applicability to problems associated with cavitating-propeller excitation, then the flow accelerating fin is the only choice of the options tested that produces an acceptable level of excitation. The rapid reduction of the pressure pulse amplitudes forward and aft of the propeller location as seen with both the tested fins for the AO-177 is an important adjunct to the SSPA criterion when it is applied to give guidance to the solution of a ship vibration problem. With the situation of the AO-177, the choice of the flow accelerating fin for the final corrective measure was made on the basis of its performance relative to the other options. It offered a likely cure for the problems while retaining the original propeller.

Both fin configurations were found to influence not only the blade rate component but also the higher harmonic content of the fluctuating hull pressure characteristics. Figure 25 is a comparison of the first three harmonic components of pressure double amplitude at several points around the propeller aperture, presented in terms of the mean of the 5 percent highest amplitudes determined from Fourier analysis. The data apply to the full-load, full power condition for the two fin arrangements and for the original AO-177. At the point on the hull directly above the propeller tip, the effect of each of the fins is to increase the second and third blade rate harmonic components $2\Delta p_{2Z}$ and $2\Delta p_{3Z}$ relative with the no-fin case. This is apparently an isolated trend, however, because for all the other points considered, both forward and aft of the tip plane, the effect of the fins is to reduce the second and third harmonic components of pressure. From spectral analyses of typical hull pressure pulses, the reductions of the 2Z and 3Z harmonic components due to the fins tend to be repeated for all the subsequent higher harmonic components up to frequencies at least as high as 1 kHz. Therefore, over most of the hull surface near the propeller, the model experimental results indicate that both fins produce lowered overall fluctuating pressure excitation in the frequency ranges important to the production of airborne noise. There seems to be no clear-cut advantage for either fin in this regard. The better performance of the flow-accelerating fin at the blade rate harmonic was the significant factor in its choice as the final corrective design modification to be installed full scale.

In addition to the model experimental determination of the cavitating propeller excitation levels of the AO-177, analytical investigations were carried out by four independent groups under contract. Some of the results are presented in Appendix 2 for the cases of the original AO-177 and its modification with the flow-accelerating fin. In general, the results corroborate what was determined in the model tests, that compared with the unmodified AO-177, the cavitating propeller induced surface force amplitudes and cavity thickness and volume are reduced with the improved wake and with the hull shape changes introduced by the fin.

Resistance and powering with the fin

Once the flow-accelerating fin was selected as the design modification for the AO-177, the resistance and powering penalties associated with it were determined by model experiments at DTNSRDC [40].

Figure 26 shows a comparison of the powering characteristics of the AO-177 with and without the flow accelerating fin for the full load displacement with trim 0.31 m (1.0 ft) down by-the-bow. The predicted delivered power requirement was increased somewhat over the unmodified hull due to a combination of increased total resistance R_T and decreased propulsive coefficient η_D with the fin. At full power, these data indicate that there would be a speed loss with the fin of about 0.2 knot, which is a smaller variation than the typical accuracy of the towing tank experiments. Corresponding comparisons of pertinent propulsive factors versus speed with and without the fin are displayed in Fig. 27. It appears that the main effect of the fin in this case is to reduce the effective wake w_T, an expected result. There is also a reduction in the relative rotative efficiency η_R and very little change in the other factors.

For the ballast condition, with trim 1.14 m (3.75 ft) down by the stern, the powering characteristics of the AO-177 with and without the fin are compared in Fig. 28. There was a measured increase in resistance with the fin, but due to changes in all the propulsive factors (see Fig. 29), the propulsive efficiency η_D is increased somewhat so that the delivered power requirements are actually reduced compared with the case of no fin. Therefore, the speed at full power is predicted to increase slightly by 0.3 knot, again a variation that lies within the typical accuracy of the experiment.

Proposed redesign of propeller

A proposed redesign of the propeller[8] was performed for the ship as fitted with the flow accelerating fin as a possible solution in the event that the fin did not solve the problems with the existing propeller. The proposed redesign considered the geometric characteristics and resulting cavitation performance of the existing propeller and of the stock propellers evaluated at SSPA. However, it is not considered to be a "final" redesign since it has not benefited from information from all the trials nor has it been tested for propulsion or cavitation performance.

[8] Described in a report of restricted distribution by S. Jessup entitled "Preliminary Redesign of the AO-177 Propeller," 1982.

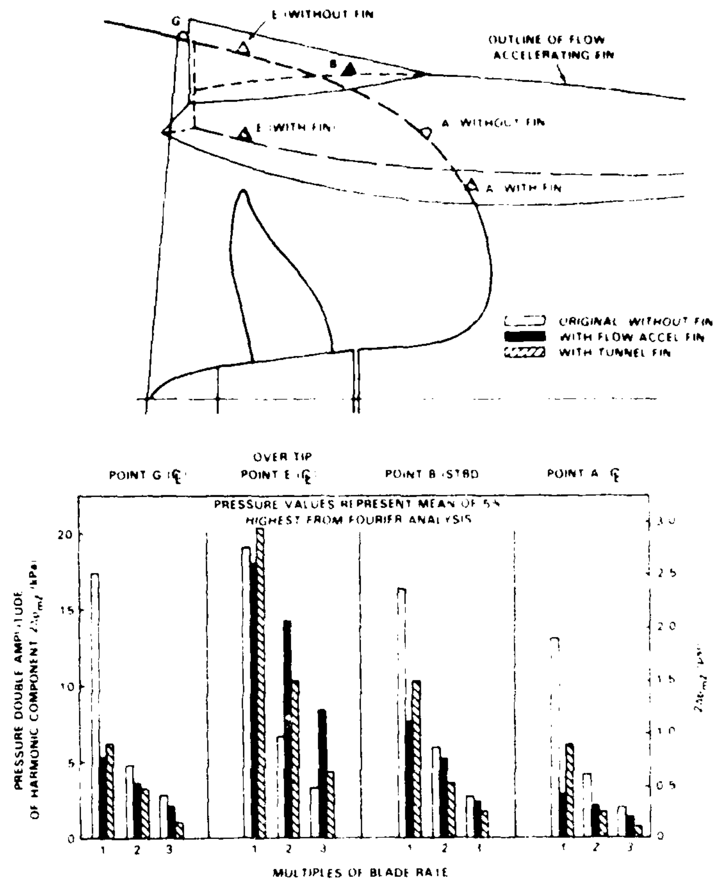


Fig. 25 Variation of major harmonic components of propeller-induced hull pressure pulses at several locations, with and without wake-improving fins

The design conditions specified for the redesign were the same as those for the original propeller (Table 3) except for modifications to minimize airborne noise and erosion. As discussed later, it was also necessary to increase the maximum allowable blade frequency bearing forces.

As discussed in a preceding section, the existing AO-177 propeller has seven blades and relatively short chords, especially near the tip; see Table 2. Although the existing propeller has 45 deg of projected skew angle at the tip, the skew angle distribution is essentially linear from the midradius to the tip. The narrow chord lengths near the tip appear to reduce the tendency of skew to reduce cavitation [41, 42] by reducing the sweepback angle of the leading edge, that is, the angle between the projected leading edge and a radial plane. The full scale cavitation observed on the AO-177 propeller showed a two-dimensional character indicative of the narrow blades, that is, little radial motion of the cavitation or interaction with the tip vortex.

A variety of geometry changes has been suggested to reduce propeller-induced hull forces and propeller erosion problems. These suggestions are summarized as follows.

1. *Increased chord length* [18]. A dramatic change in this parameter could be achieved because of the abnormally short chords at the outer radii of the existing propeller. Increasing chord lengths would reduce the loading per unit area on the blades, thus reducing the volume of cavitation. Reducing the number of blades for the same expanded area ratio would produce wider blades, possibly causing a greater three-dimensional cavity structure and reduced violence of collapse. Also, fewer blades would bring the design closer to traditional design practice.

2. *Large skew variation near the tip*. A large variation (gradient) in projected skew angle θ_s near the blade tip will produce a highly swept tip. This type of blade outline, when heavily loaded (as occurs in the wake peak), may induce turbulent separation along the leading edge extending to the blade tip. If this occurs, then cavitation forms along the leading edge and will be convected into the tip vortex and off the blade. It is believed that blade cavitation collapses gently off the blade when it merges with the tip vortex. This process has been observed by Jessup [43] and on the five-bladed stock propeller (Propeller A) evaluated on the AO-177 model hull at SSPA. This type of blade outline has been successfully adopted with controllable pitch propellers for commercial ship applications with significant reductions in propeller-induced hull vibration [13].

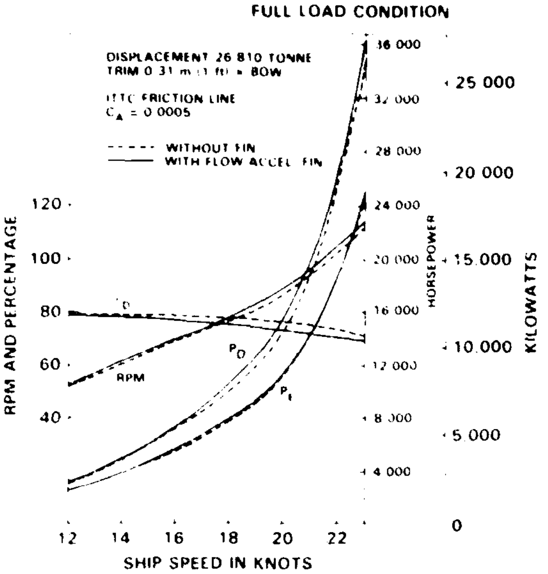


Fig. 26 Comparison of resistance and powering properties with and without flow-accelerating fin for trial full-load displacement

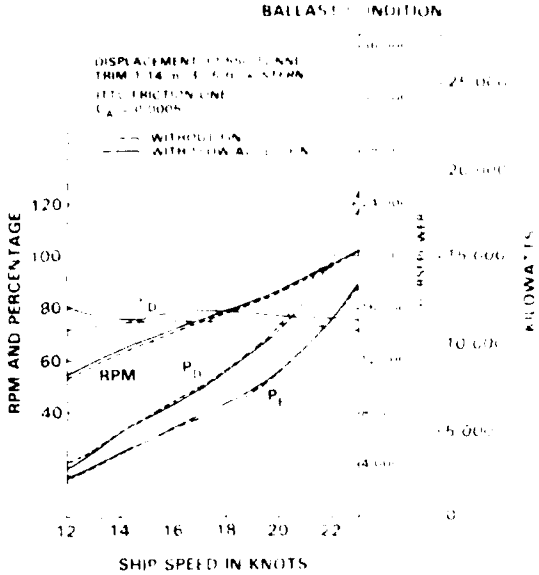


Fig. 28 Comparison of resistance and powering properties with and without flow-accelerating fin for ballast condition

3. Increased loading near the tip 18. Increased loading near the tip will increase the cavitation volume, and the blade angular extent in which cavitation occurs. This may tend to decrease erosion and the violence of the cavitation collapse, but too much loading near the tip may increase the propeller induced hull forces.

4. Reduced loading near blade tip 18, 44. In general, reduced loading near the blade tips will reduce the amount of cavitation. Propeller induced hull forces may be be reduced, however the effect of tip unloading on cavitation erosion and cavity collapse is not fully understood. In some cases, tip unloading produces undesirable unstable cavity collapse.

5. Increased angle of attack loading with decreased camber loading 18. Blade pitch can be increased with a corresponding decrease in camber, resulting in unchanged propulsive performance. This will alter the pressure distribution on the blade sections, providing a less severe chordwise pressure gradient near the trailing edge, which may reduce the violence of the cavity collapse.

The approach chosen for the proposed redesign of the AO 177 propeller incorporates Items 1, 2 and 4, increased chord lengths, an increased skew gradient, and slightly increased loading are incorporated near the tip region. Time average chordwise loading corresponding to an NACA a = 0.8 mean line at ideal angle of attack was specified, which is the same as was specified for the existing AO 177 propeller.

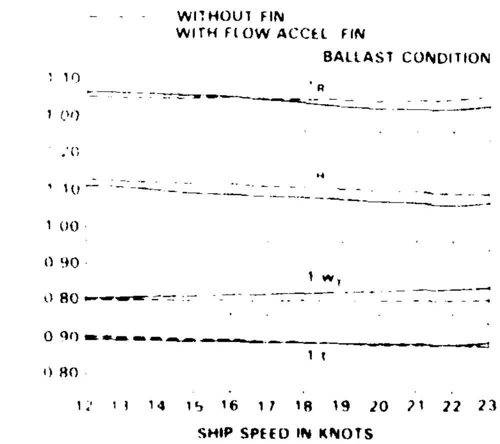


Fig. 27 Comparison of propulsive coefficients with and without flow accelerating fin for trial full load displacement

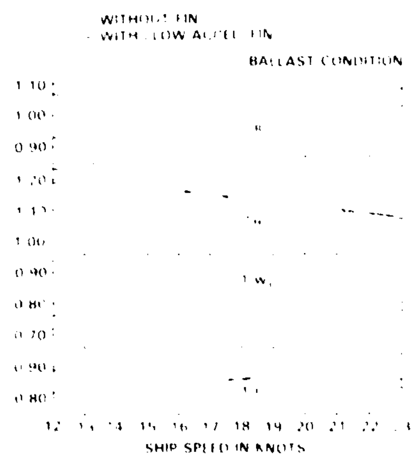


Fig. 29 Comparison of propulsive coefficients with and without flow-accelerating fin for ballast condition

Calculations of the blade frequency bearing forces with and without the fin were made using the same methods used for the design of the existing propeller and using model wakes with and without the fin (see Fig. 34). The limitations of these methods were discussed in the earlier subsection on propeller details and design. These calculations indicate that in order to meet concurrently the following two requirements specified for the original design:

1. produce blade frequency thrust [illegible] that is less than 13.3 kN (3000 lb), and
2. have a blade planform with neither a [illegible] trailing edge [illegible] edge near the [illegible]

[illegible] the same [illegible] original design. This [illegible] from the [illegible] the pertinent wake harmonics with and without [illegible] (see Fig. 34) and the [illegible] blades increase [illegible] existing propeller. Therefore [illegible] for improving airborne noise and erosion, the bearing force limits had to be increased and the subject of [illegible] trailing edge [illegible] had to be [illegible].

Full-scale measurements [illegible] indicated that the longitudinal [illegible] resonance [illegible] the AO 177 occurs at [illegible] Hz, or [illegible] above the full power [illegible] with a seven-bladed propeller, rather than at approximately [illegible] Hz as was predicted when the original design was carried out. Therefore, the maximum allowable blade frequency thrust to meet MIL-STD-167 increased with decreasing number of blades, with the [illegible] limit being [illegible] kN (3000 lb) for seven blades and 35.6 kN (8000 lb) for five blades. In addition, measurements [illegible] no significant hull vibration due to transverse bearing forces; therefore, the restriction on transverse bearing forces were substantially relaxed.

Four blades were unacceptable for the same reasons as for the original design, and seven blades would force the design to be almost the same as the existing design. Full-scale measurements and additional response calculations made since the original propeller design indicate that excessive hull girder vibration is no longer considered likely with a five-bladed propeller. Five blades were selected rather than six because blade frequency for a five-bladed propeller is farther from the longitudinal resonance in the main propulsion system and because it allows wider chords to be used near the tip than does a six-bladed propeller.

Due to reduced clearance with the fins and other constraints as discussed for the original design, the diameter had to remain at 6.4 m (21 ft).

The design process involved choosing a blade outline to maximize sweepback of the blade leading edge near the tip with wide chords near the tip subject to the following constraints:

1. Avoid a pointed tip trailing edge from consideration of strength and damage susceptibility, especially during astern rotation.
2. Maintain periodic bearing forces to the new specified values.
3. Avoid the blade overhanging the front and back edges of the hub.

The proposed blade shape representing the best compromise of these characteristics is shown in Figure 30. The bearing forces for the redesign propeller predicted using the same procedures as for the existing AO 177 propeller are given in Table 11.

The loading near the tip was slightly greater than it was for the original design but slightly less than the Lerbs optimum. This distribution was selected in an attempt to reduce the violence of the cavity collapse without excessively increasing the loading near the tip. The radial distribution of thickness was

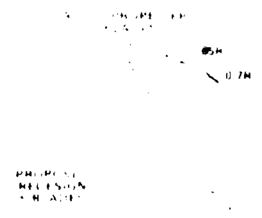


Fig. 30 Comparison of existing propeller with proposed redesign

selected in conjunction with the radial distribution of loading to ensure a 30 percent margin on inception of back bubble cavitation at full power, adequate freedom from face cavitation at [illegible] power, and strength integrity.

Figure 30 compares the geometries of the existing propeller with the redesigned propeller. The slightly smaller tip skew for the redesigned propeller resulted from the requirements to avoid a pointed blade profile near the tip and to have wide chords near the tip. The predicted propulsion performance of the two propellers are essentially equal.

Det norske Veritas, using a procedure based on [illegible] lifting surface theory, including the influence of cavitation, predicted that the proposed redesign propeller would reduce the blade rate hull pressures to approximately 70 percent of the values with the existing propeller. This reduction is predicted both with and without fin. In addition, DnV predicted that the proposed redesign would be erosion free on the ship as fitted with the fin.

Full-scale verification

Following the installation of the flow accelerating fin on the AO 177 at Todd Shipyards in Alameda, California, the ship was instrumented for measurements of airborne noise, fluctuating pressures on the fin underside, main shaft torque, and propeller viewing.

Airborne noise

The general result of the fin installation is a reduction in compartment octave band noise levels by 10 dB or more in spaces aft of Frame 94. In some areas, such as the [illegible] [illegible] served. Typically, the noise levels dropped from being significantly greater than specification criteria to being within the criteria.

Example comparisons of the noise levels in four critical spaces before and after the fin installation are given in Figs. 31 through 34. Included are the applicable Navy specification criteria levels for these spaces. Figure 35 is a sketch of the ship aft end inboard profile showing a comparison of averaged low fre-

Table 11 Calculated bearing forces on proposed redesign propeller

	SEI Procedure [illegible] Model Nominal Wake		DnV [illegible] Model [illegible]	
	kN	[illegible]	kN	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]		[illegible]

Calculated by DnV

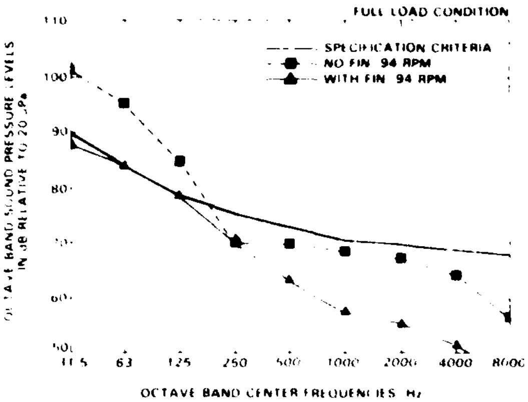


Fig. 31 Airborne noise levels before and after fin installation, Crew Berthing and Dressing No. 6

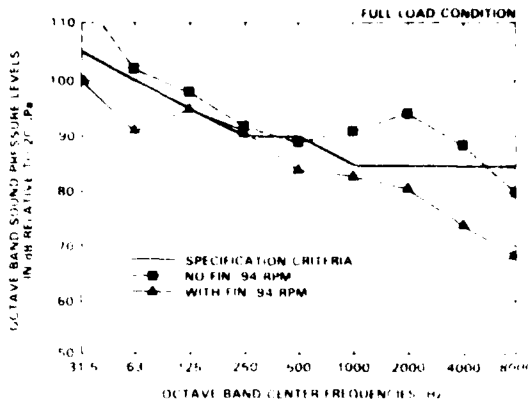


Fig. 33 Airborne noise levels before and after fin installation, Steering Gear Room

quency noise levels in several locations and how they varied with distance away from the propeller vicinity.

Dependence of airborne noise upon ship speed (or rpm) is illustrated in Fig. 36, which shows the noise levels measured in the steering gear room at 45, 75, 90, and 100 rpm for the ship in ballast condition.

In some of the living spaces, the propeller noise still remains subjectively annoying or at least noticeable and distracting, even with the significant reductions produced by the fin attachment. The annoyance factor may be related to the temporal characteristics of propeller noise being modulated at blade frequency, or possibly modulation due to ship motions in a seaway. Also, it must be pointed out that despite the satisfactory reductions of the noise to values at or below the applicable criteria levels in Table 5, the AO-177 can be judged to be a noisy ship. Quite independent of the AO-177 issue, the U.S. Navy has taken action recently to lower its acceptable noise level criteria to the values shown in Table 12, and by these new standards (not applicable retroactively), there are spaces on the AO-177 that would require further attention to produce a completely satisfactory fix.

Full-scale propeller cavitation

Propeller viewing and photography were carried out using the same periscope system that was rigged for the earlier trial.[7] The visibility and photography were not as clear, however, due to the shadow of the fin, overcast weather, and poorer water clarity.

The results discussed here are for the full load, full power condition. Example comparisons of the appearance of cavitation without and with the fin installed are shown in Fig. 37. The line sketches were prepared as composites from many photographs, and are provided here for both the cases without and with the fin. Corresponding sample photographs are included only for the case without the fin. At an angular position of approximately 35 deg past the upward vertical (Fig. 37a), the cavity without the fin appears to be thicker and extends over slightly more of the blade than the cavity with the fin. At 50 deg past vertical, the cavity without the fin forms a large, thick

[7] More details are presented in a report [illegible] T.Y. Koh and S.D. Jessup, entitled [illegible] AO-177 [illegible] Trial, Feb. 1982.

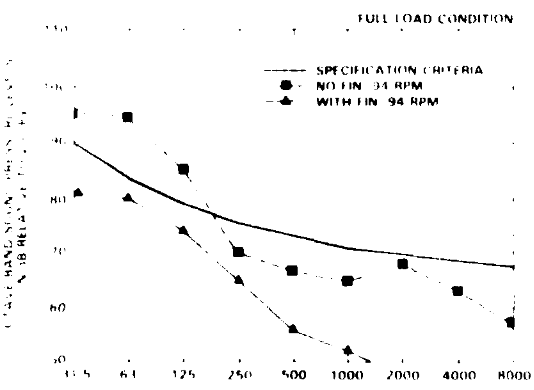


Fig. 32 Airborne noise levels before and after fin installation, Crew Berthing and Dressing No. 4

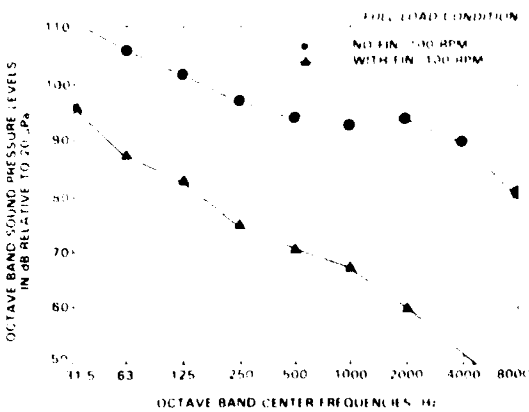


Fig. 34 Airborne noise levels before and after fin installation, Fantail-Main Deck

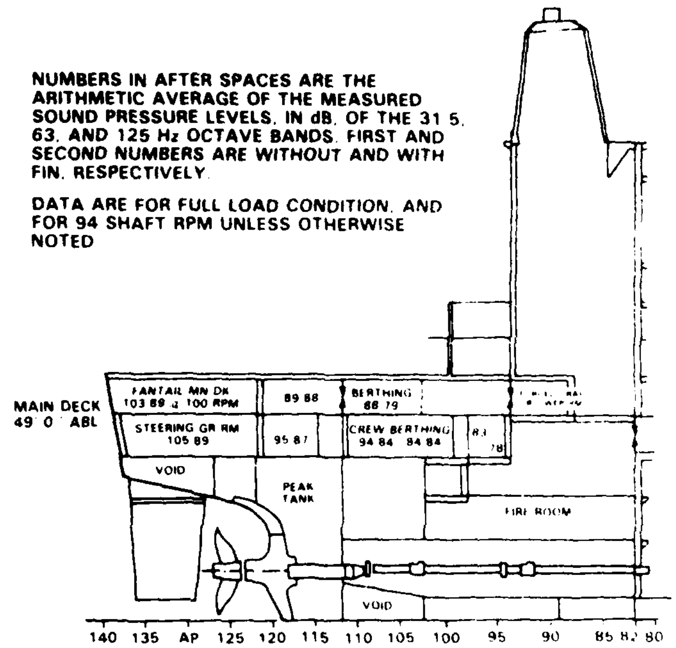


Fig. 35 Variation of averaged low-frequency noise levels in stern region before and after fin installation

cloud behind the trailing edge which breaks into two separate tip vortices. With the fin, a thinner, more-uniform sheet extends downstream into a single vortex. At 65 deg past vertical (Fig. 37(b)), the blade is approximately 5 deg ahead of the estimated point of cavity collapse. For the case without the fin, a substantial cloud of cavitation can be seen to form behind the cavity sheet, *presumably* broken off from the cavity sheet at a previous instant.

The effect of the fin appears to have reduced the cavity volume, *mainly by reduction of cavity thickness*, because of the reduction of the maximum wake defect and the resulting decrease in the angle of attack variation on the blades, especially near the tips. This has *the effect of reducing both the excursions* of low-pressure fluctuations near the leading edge and the production of cavitation.

Propeller erosion tendency

The propeller was inspected in dry dock five months after the fin evaluation trial. At this time, approximately 50 hr of running at high power levels had been logged since the fin and a replacement propeller (original design) had been installed. No evidence of bending of the trailing edges was found. No erosion due to cavitation was detected, but some minor *dimpling and burnishing* of the suction side (back) surface near the tips could be seen after the blade tips were washed to remove deposits. It was decided, based upon this inspection, that *no further* action regarding the propeller was necessary, except for the periodic inspection of the propeller blades.

Propeller-induced pressure pulse amplitudes

Measurements of the blade rate pressure amplitudes were made at several points on the fin underside at locations somewhat off the centerline that have minimum radial tip clearance. Figure 38 shows the longitudinal distribution of blade rate pressure double amplitudes, comparing model experimental results with the *full scale trial measurements* at full power [illegible] load. The model results are the maximum oscillograph recorded values of $2\Delta p_z$, including the cases with and without the flow accelerating fin. The full scale trial results represent three different runs at 100 rpm with the [illegible] values converted to equivalent double amplitudes by multiplication by $\sqrt{2}$. Although there is scatter in the full scale data and some differences between the average [illegible] model data, the general trends and correlation [illegible] are encouraging, and seem to verify the benefits [illegible] fin.

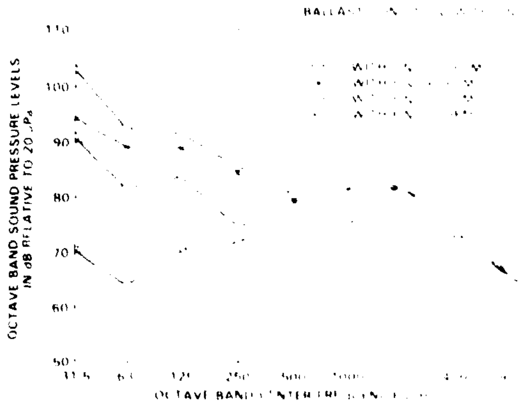


Fig. 36 Variation of airborne noise levels [illegible] Steering Gear Room

Table 12 New Navy noise criteria levels—permissible airborne sound pressure levels (in dB relative to 20 μPa)

Type of Space	32	63	125	250	500	1000	2000	4000	8000
	Octave Band Center Frequency, Hz								
Large command and control	72	69	66	63	60	57	54	51	48
Small command and control, and administrative spaces	81	78	75	72	69	66	63	60	57
Medical	78	75	72	69	66	63	60	57	54
Shops, service spaces, passages and topside stations	88	85	82	79	76	73	70	67	64
Machinery	97	94	91	88	85	82	79	76	73

Operating experience

Operator feedback with the fin installed has been good. With the crew comfort improved, the ship has been run extensively with no speed restrictions, it has experienced no adverse effects on its maneuvering properties, and it has engaged in numerous underway replenishment operations. As noted earlier, the propeller erosion tendency has been noticeably reduced compared with the builder's trials performance. The ship has been shown to be acceptable for fleet duty in its intended mission.

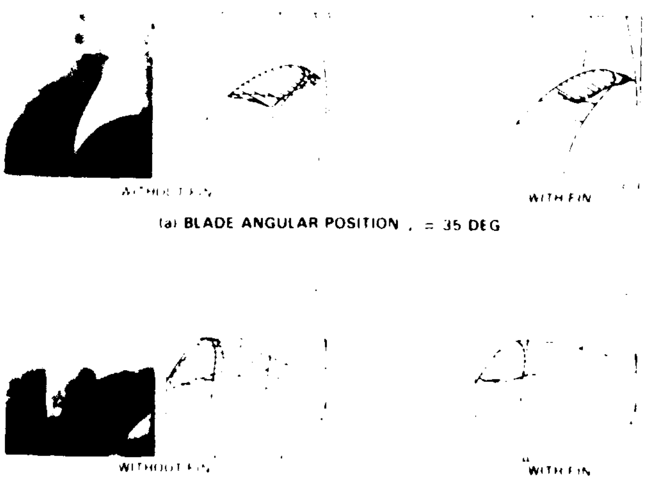
Conclusions

The following conclusions directly applicable to the AO-177 were drawn from the noise correction program.

- Fluctuating pressure pulses from intermittent blade cavitation caused the propeller excitation problems of the AO-177. The situation was attributable to the combination of a poor wake due to the after hull shape, excessive unstable cavitation on the unfavorable propeller blade geometry, and the relatively high speed and power.
- The flow-accelerating fin configuration was effective in reducing blade rate hull surface pressure excitation due to reductions in propeller cavitation caused by improvement in the magnitude and steepness of the nominal wake. The fin also produced reductions in higher blade rate harmonic components (model scale) of the pressure pulse excitation, and this trend is likely responsible for reductions in structureborne noise and vibration that eventually radiate energy as diminished airborne noise inside the ship.
- The flow-accelerating fin produced a significant reduction of inboard airborne noise on the ship, to levels within the specifications.
- The propeller blade erosion tendency was measurably reduced by the flow-accelerating fin configuration.
- The flow-accelerating fin configuration produced negligible penalties on the drag and propulsion characteristics of the ship.
- Model experiments indicated that reductions of propeller-induced hull pressures could be achieved with propeller design modifications.
- It is speculated that a combination of a flow-improving fin and redesigned propeller could provide even lower surface pressure and surface force excitation than was achieved with the flow-accelerating fin alone, but with likely increases of periodic thrust and torque beyond the tight constraints.

Other conclusions and recommendations are:

- The criteria for periodic thrust that dictated important



(a) BLADE ANGULAR POSITION , = 35 DEG

(b) BLADE ANGULAR POSITION , = 65 DEG

Fig. 37 Comparison of AO 177 propeller cavitation (full scale) with and without fin

details of the AO-177 propeller geometry may have to be relaxed somewhat for single-screw auxiliary ship designs.

• The excitation from propeller induced hull surface pressures and forces should be determined routinely along with bearing force and moment excitation as part of the ship and propeller design process, especially for single-screw ships with appreciable wake.

• Great care must be exercised when the nominal wakes are predicted to exhibit large and steep peaks. Bulbous sterns or open stern arrangements should be considered seriously in early stage design.

• Crew accommodations and other occupied spaces where critical criteria must be met should be located as far from the propeller as practical, such as in the deckhouse superstructure or well forward.

Acknowledgments

The work described in the paper could not have been successfully accomplished without the contributions of many organizations and individuals whose efforts the authors gratefully acknowledge; however, it would be impractical to name all of them. The authors would like to express their special appreciation to Stuart Jessup, Gary Hampton, Bob Perkins, Chris Noonan, Jerry Kelley, Don Drazin and In Young Koh from DTNSRDC for valuable contributions to model experiments and full scale trials; to Brian Corbin of DTNSRDC for prediction and analysis of the vibratory response of the main propulsion system; and to Dan Nelson of BBN for his work on the evaluation trial. Stuart Jessup also conducted the proposed redesign of the propeller. The staff at SSPA in Goteborg, Sweden, especially E. Bjarne, Carl Anders Johnsson and Gilbert Dyne, have our particular thanks for their expert guidance with model experiments and the benefit of their experience with propeller excitation problems. Considerable benefit was derived from calculations performed at Det norske Veritas (DnV) and from consultations with the staff of DnV, especially Arnst Raestad and Hans Smogeli. Valuable advice and design assistance were provided by Roger Schaeffer, Otto Scherer, and Jeffrey Bohn of Hydronautics, Inc. Finally, Captain Black and the crew of the USS *Cimarron* have our gratitude for their patience and support during the various sea trials.

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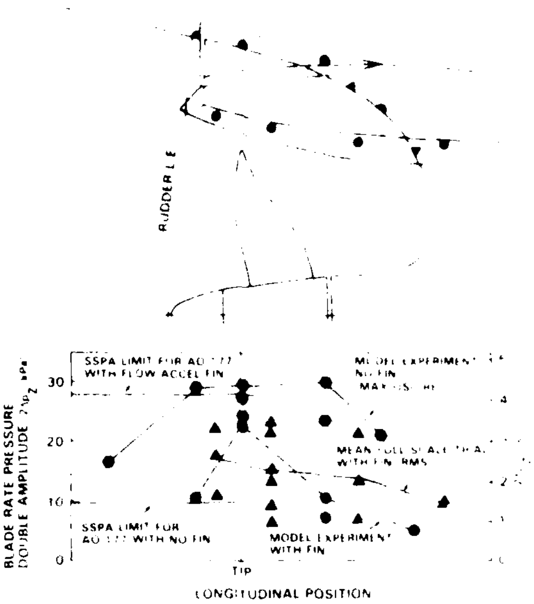

Fig. 38 Comparison of longitudinal distribution of blade rate pressure pulse double amplitudes: model experiments and full scale

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Appendix I

Measurement and analysis of airborne noise

All airborne noise measurements aboard the AO 177 were made with portable instrumentation consisting of sound level meters with octave band analysis capability, and condenser microphones. The noise data were manually tabulated. Where noise levels varied with time, the meter display was visually averaged over a period typically in excess of 10 seconds for each data entry. This approach was used consistently during all the trials where airborne noise was measured, and comparison of the data with compartment noise criteria is considered valid.

Airborne noise measurements were taken at locations representative of manned positions within the various surveyed compartments. In berthing and dressing spaces, measurements typically were taken near two bunks. Measurement locations were selected on the basis of commonality with the builder's trials noise survey.

The Navy's airborne noise level criteria are assigned to shipboard spaces on the basis of compartment operational requirements. Depending on the functional nature of the space, the noise criteria are intended to minimize personnel hearing damage risk (for example, in machinery spaces), allow reliable speech communication (as in office and command and control spaces), and provide for reasonable habitability in living, mess, and recreational areas.

Table 5 shows the specific airborne noise criteria, in octave band levels, which were included in the AO 177 ship building specification. Recent changes in occupational noise control and hearing conservation requirements have established acceptable noise levels for ship spaces which are considerably lower than levels used in the AO 177 and other specifications which were written prior to 1981. To comply with public law and other operational needs, the Navy formally set maximum allowable airborne noise levels for six different categories of shipboard spaces. These criteria, first established as dBA levels and then expanded to octave band levels, are shown in Table 12.

Appendix 2

Results of analytical investigations

As part of the program of investigations for finding and verifying a cure for the problems of the AO-177, predictive calculations were commissioned from several independent sources to study the propeller blade cavitation, and estimate the propeller-excited hull pressures and surface forces. This work was undertaken to

- provide corroborative evidence on the character of the initial cavitating propeller flow and its alteration by the proposed fix
- obtain some idea of the correspondence between levels of propeller-induced hull pressures and hull surface forces that give rise to troublesome excitation, and

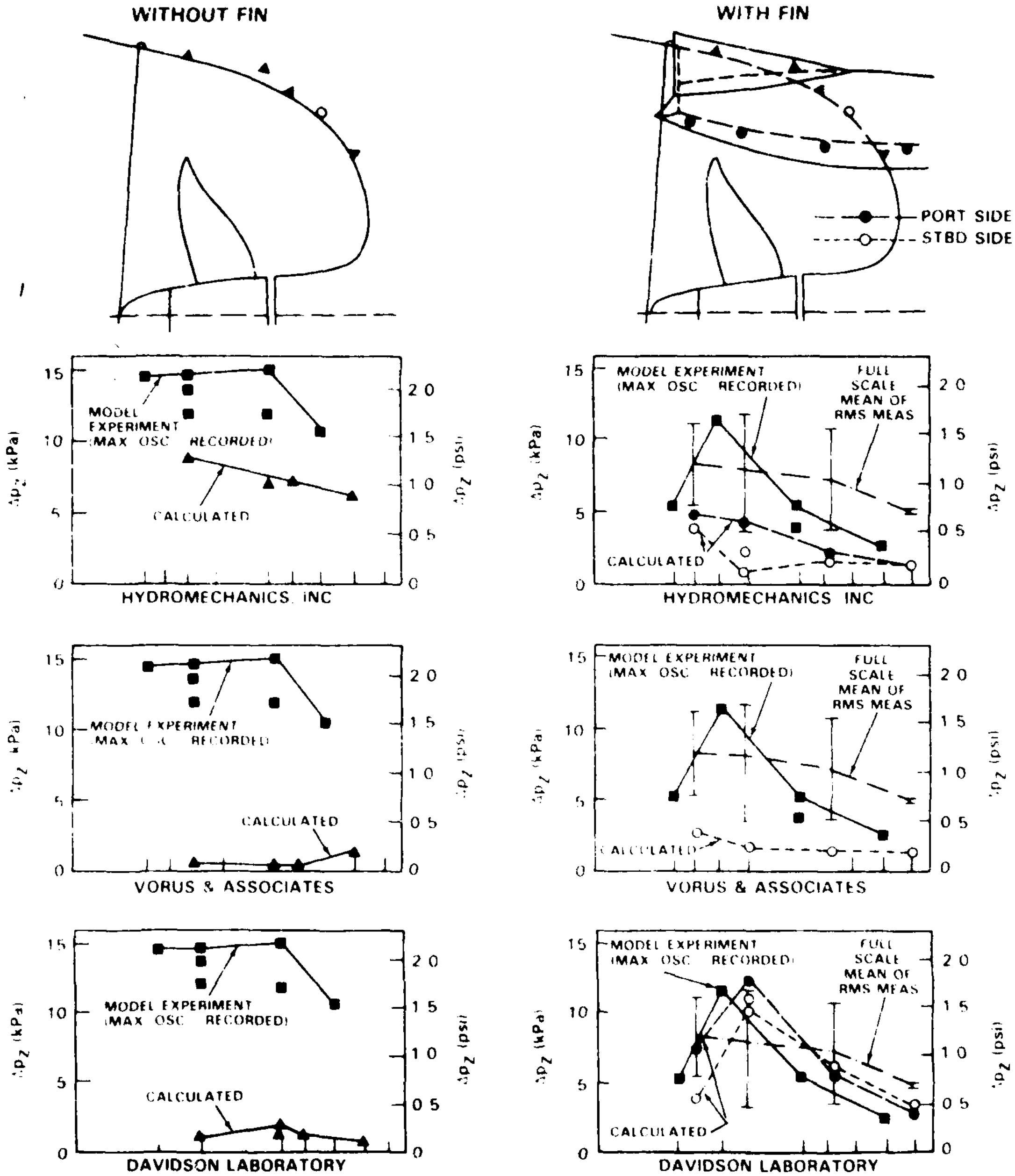


Fig. 39 Computed distributions of blade rate pressure amplitudes with and without fin

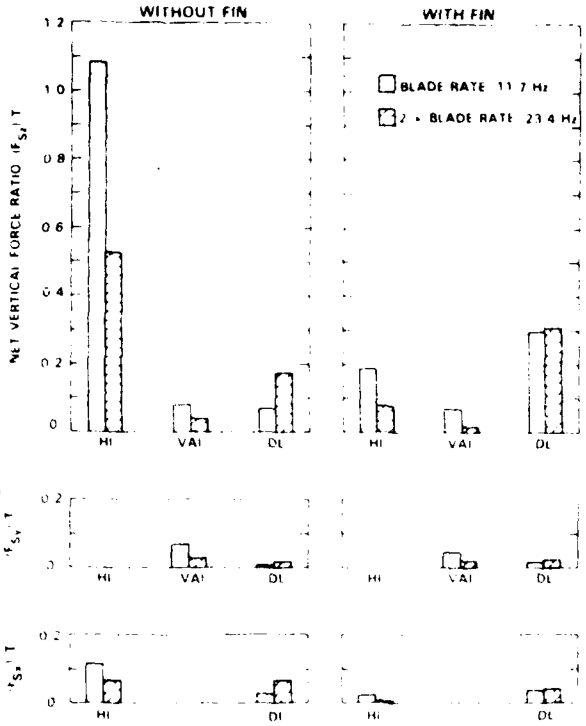


Fig. 40 Predictions of fluctuating hull force components

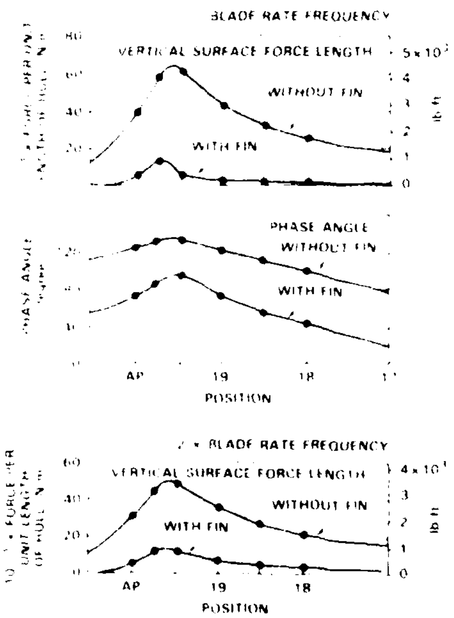


Fig. 41 Computed predictions (from DnV [9]) of vertical surface force per unit length at blade rate and twice blade rate, with and without flow-accelerating fin

- obtain correlations between measured and predicted cavitation patterns and hull pressures on a realistic example

Ship and propeller geometry and speed power data corresponding to the full-power, trial full load conditions for both the original AO-177 and for the AO-177 with the flow accelerating fin were supplied to the Davidson Laboratory (DL), Hydromechanics, Inc. (HI), Vorus and Associates, Inc. (VAI), and Det norske Veritas (DnV). These groups performed similar calculations using their existing procedures.

The Davidson Laboratory results [45, 46] were obtained using a full propeller analysis program [47] which accounts for the boundary reflection effects of the hull shape. The necessary velocity potential inputs appropriate for a cavitating propeller were determined using a quasi-steady, two-dimensional cavity flow theory and an approximated propagation function to model the effect of the entire propeller. The DL approach made possible the simulation of either a rigid free-surface condition or a pressure free surface condition at the location of the zero speed waterline.

The results from Hydromechanics, Inc. [48, 49] were carried out using the approach described in reference [50] which employs a quasi-steady flow analysis to model the cavitating blade sections and a strip theory to describe the effects of the entire propeller. A lifting-line solution was used in this case to obtain the steady loading solution needed to estimate the noncavitating effective camber and angles of attack. The resulting fluctuating free space pressure field values were multiplied by a factor of two to account approximately for the presence of the body.

The results of Vorus and Associates, Inc. [51, 52] were carried

out with the theory described in reference [53]. The reciprocity theorem employed by Vorus recasts the problem into a form such that the surface forces are calculated directly rather than by means of integrating the pressures over the hull surface. Hull shape effects on the local boundary reflection properties are accounted for. Fluctuating pressures are computed independently of the basic surface force calculation scheme. The calculations also employ an unsteady cavitation dynamics analysis to solve for the effects of cavity cross-sectional area variations to be superposed on the noncavitating blade loading effects.

The DnV results [9] employ an unsteady, noncavitating vortex lattice lifting surface theory for the blade loading effects using an approximate accounting for effective wake. Unsteady cavitation effects are modelled with time dependent source distributions over the panels of the lifting surface. The final free space fluctuating pressure values were multiplied by a factor of two to account for the presence of the hull near the propeller.

These methods were (and still are) in various stages of development; therefore some of the results are to be viewed as preliminary and in need of further refinements.

Longitudinal distributions of blade rate pressure amplitudes at points along the upper aperture are shown in Fig. 39, comparing results of three of the predictive methods. For the case with fin, the points of interest are off the centerline where the fin undersurface is closest to the propeller disk. There is a dramatic variation in the magnitudes of the pressures predicted by the various calculation schemes. For the case without the fin, all the calculation procedures predict pressure amplitudes that are substantially [illegible] than those measured in the SSPA water tunnel. For the case with the fin, the predictions are somewhat closer to model and full scale measurements. As discussed previously, the full scale data have considerable scatter.

Figure 40 presents the predicted blade rate and twice blade rate harmonics of the net surface force component amplitudes induced by the cavitating propeller as decimal fractions of the time average propeller thrust T. Again there is considerable variation in the amplitudes predicted by the various methods. For the case without the fin, predictions from DL and HI indicate that vertical force is more than a factor of 10 greater than the athwartship force, whereas VAI predicts that the vertical force is only slightly larger than the athwartship force. DL and HI predict that the vertical force is substantially larger than the axial force, and VAI did not include the axial force.

For the important vertical surface component F_Z, HI predicts that the blade rate amplitude without the fin is greater

Table 13 Calculated effect of fin on vertical surface force component

Prediction Method	[illegible]	[illegible]
DnV	[illegible]	1
HI	[illegible]	[illegible]
VAI	[illegible]	[illegible]

than the propeller thrust and more than 10 times greater than the corresponding predictions by DL and VAI. The predictions of the blade rate harmonics of vertical force by DL and VAI are in good agreement; however, the twice blade rate amplitude predicted by DL is over [illegible] times as large as that predicted by VAI.

Det norske Veritas [9] did not calculate net surface force components, preferring instead the prediction of vertical surface force per unit length shown in Fig. 41. From this, the trends of the vertical surface force calculated by DnV can be compared with the corresponding trends predicted by the other three methods. HI, VAI and DnV predict that the amplitude of the blade rate vertical force is greater than the twice blade rate amplitude; however, DL predicts the opposite trend. All the methods that were exercised for both wakes with and without the fin predicted that the fin would reduce the blade rate amplitude of the vertical surface force; however, the amount of reduction varied substantially between the various methods and are summarized in Table 13. Additional information was provided from [illegible] on the blade cavitation patterns [illegible] properties. In general, all of these predicted that by fitting the fin the blade cavitation extent was reduced and the cavity [illegible] velocities were diminished relative to the characteristics of the unmodified AO 177. Det norske Veritas [9] also provided the results of a calculation of the spectrum of the propeller unsteady source strength sound pressure level with and without the flow accelerating fin. With the fin substantial reductions of the excitation pressure levels were predicted relative to the original AO 177, covering a range of frequencies up to [illegible] kHz.

It is beyond the scope of the present paper to attempt to explain the variations in the predictions shown earlier in this Appendix. In the opinion of the authors, however, these discrepancies are representative of the present state of the art. Intensive research and development directed at improving the capability to calculate the propeller-induced periodic hull pressures, surface force distributions and net surface forces is strongly recommended.

Discussion

E. Bjarne, [illegible] Visitor

I would first like to congratulate the authors on an excellent paper covering most, if not all, aspects involved in the problem. It is interesting to notice that the model test results have given good correlation with the full scale measurements, which apparently is not always the case with the theoretical calculations. It is also encouraging that the desired improvement with regard to the vibration and noise problems has been achieved with the recommended measures.

The paper covers most details involved, but it would have been of interest to have some information about especially the full scale blade frequency vibration velocities in the extreme aft region, if those were measured.

The improvement [illegible] pressure [illegible] celerating fins is according to the [illegible] trated in the blade frequency [illegible] plitudes are only [illegible] the airborne noise at full scale [illegible] noticeably lower with [illegible] than without [illegible]. The former values, however, refer to the [illegible] amplitudes. If the mean values from the model tests are compared, better correlation between the model [illegible] and the full scale noise measurements will be obtained. Furthermore, it could not be excluded that some of the noise is caused by rattling of construction details excited by propeller-induced pressure pulses of lower frequency.

The erosion obtained on the [illegible]-bladed propeller was also verified by the model tests. This erosion may possibly be ex

[illegible] Swedish Maritime Research Centre, SSPA, Göteborg, Sweden.

[illegible]

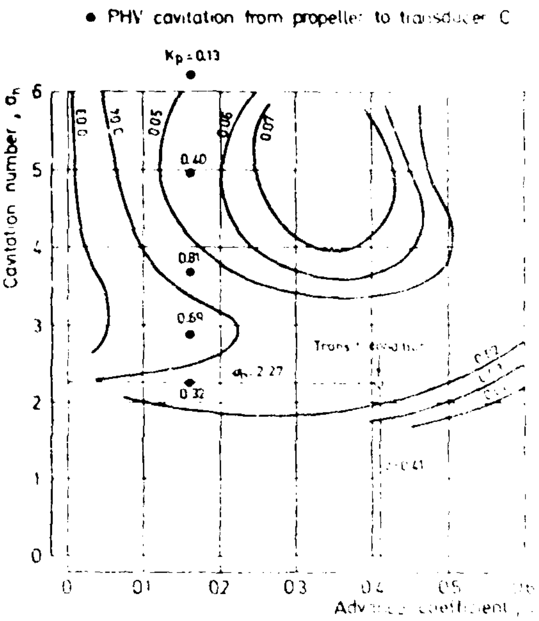


Fig. 42 Influence of PHV cavitation on pressure pulse [illegible]

[illegible] by the relative [illegible] camber pitch relation for the propeller concerned. Usually when we design a propeller according to the vortex theory, corresponding relations between pitch and camber are obtained, see for instance the stock Propeller A in Fig. 21, for which the reduced blade tip pitch is reflected by a similarly reduced profile camber. This relation may, however, be influenced by the shape of blade (skew back) and wake distribution for the design, but still the blade tip profile of AO 177 seems to be somewhat over-cambered.

At tests with nozzle in front of the propeller model, [illegible] vortex cavitation between the blade tips and the inside of the duct was noticed. To show the pressure pulses created by such [illegible] cavitation, Fig. 42 is presented [illegible] additional references [illegible] concerned the vortex cavitation (PHV) [illegible] blade tip happened [illegible] the [illegible] The pressure pulse [illegible] of excitation forces [illegible] amplitudes [illegible] times the [illegible] areas.

Additional reference

[illegible] Bjarne [illegible] and Meitz [illegible] Propellers for a Semi-Submersible Offshore Support [illegible] Paper No. 24, International Offshore Conference, Gothenburg, Sweden, [illegible] 1981 [illegible]

A. Zaloumis, Member

The views expressed herein are the opinions of [illegible] necessarily those of the Department of Defense [illegible] the Navy.

I wish to address my remarks to the empirical factors that are applied to the calculated propeller unsteady thrust force.

Design stage calculations of propulsion systems include the analysis of longitudinal vibrations which describe the response of the system to propeller alternating thrust forces. Estimates of these propeller forces in the design stage are accomplished by one or more of the following methods:

a) Using full-scale results from similar ships.

b) Using model wake survey data together with a propeller theory calculation scheme.

c) Performing propeller thrust variation measurements on model ships.

The method most commonly [illegible] (*b*) above because it allows [illegible] parametric variations such as number of blades, skew, and diameter. The candidate propeller [illegible] recommended on the basis of minimal exciting force and [illegible] response of the propulsion system, and built [illegible] calculations are made.

When using [illegible] longitudinal [illegible] calculation [illegible] phenomena observed [illegible]

[illegible] degrees of modulation [illegible] the upper [illegible] percent [illegible] time average values.

[illegible]

A. E. Rosstad

[illegible]

may be some nonlinear effects between the three factors so that the maximum factor is less than 27. However, I cannot see that there has to be any relation at all between the thrust variation of blade frequency steady ahead condition and, for example, the thrust variations in hard turns.

Secondly, even if such relations exist, it is, in my opinion, not possible to predict thrust variations within 1 percent accuracy keeping in mind the nature of the problems such as scaling of the wake and the time variations in the wake. These are always present and make it difficult even to quantify these small variations on the ship.

Regarding the choice of number of propeller blades, I miss the evaluation of the risk of exciting the natural frequency of superstructure, which is considered to be very important.

I also wish to comment on Appendix 2 where it is said that, for the case without the fins, all the calculation procedures predict pressure amplitudes which are substantially smaller than those measured in the SSPA water tunnel. If the DnV calculations had been included in Fig. 39 we would have seen that these results give somewhat larger pressure amplitudes than the model experiments.

Since the problems also were related to erosion, I miss a comparison between analytical and experimental amounts of cavitation.

The authors have demonstrated in an instructive way how analytical and experimental investigations can be applied to solve propeller cavitation related problems and I agree with the conclusions arrived at to solve the problem. However, this case also demonstrates the need for analytical methods to predict the propeller-induced noise at the design stage. In this connection it may be mentioned that by the DnV analytical method the noise reduction in the steering room was estimated at 10–15 dB(A) by mounting fins [9].

Finally, just a small comment on the title of the paper. According to common terminology this is a typical structureborne noise problem—not airborne.

K. Takekuma,[2] Visitor

The authors are to be congratulated for their interesting paper describing their extensive hydrodynamic investigations to find the cause of airborne noise phenomena experienced on a ship of relatively small block coefficient. As the authors explained in their paper, many vibration problems have been experienced in the past several years in spite of the effort to decrease the level of vibration and airborne noise during the course of ship design.

The discusser, who presented his experience in a paper for RINA in 1979 [55], would like to offer the following comments and questions on the basis of his experience in the design of hull forms and propellers.

1. On reviewing the propeller design of the AO 177, it is noticed that (a) the diameter of the propeller was much smaller than optimum (about 7 m), or the number of revolutions should have been higher (about 120 rpm) for the selected diameter, and (b) the expanded area was smaller than by existing criteria such as those proposed by NSMB as follows:

AE according to NSMB: 28.5 m²
AE adopted: 24.8 m²

Thus, some propellers with larger expanded area could be worth investigation in addition to the three candidate propellers A, B and C.

2. The discusser considers that higher blade rate frequency components of propeller exciting force are more responsible for the airborne noise, but Fig. 25 shows that the level of blade rate frequency component is much higher than those of higher blade rate frequency components except at over tip point A. Would the author explain how they reached the understanding on the phenomena that airborne noise is much more dominant than vibration level, although high blade rate frequency components of exciting force were relatively small?

3. Regarding the results of resistance and propulsion tests, the results shown in Figs. 26 and 27 coincide with some of our experience, namely, little difference of EHP's and thrust deduction coefficient, decrease of wake fraction coefficient and little difference of power when fitted with fin. However, the results in Figs. 28 and 29 indicate that improvement of propulsive performance is obtained by a remarkable increase of relative rotative efficiency. How do the authors explain the difference in the effect of stern tunnel fin on propulsive performance of the ship?

4. Significant variation of the full scale measurement of pressure fluctuations is shown in Fig. 38. The authors explained that those results were obtained in three runs at 100 rpm in the full scale trial. Would the authors explain the reason for the significant variation of the pressure fluctuations when fitted with a fin?

Additional reference

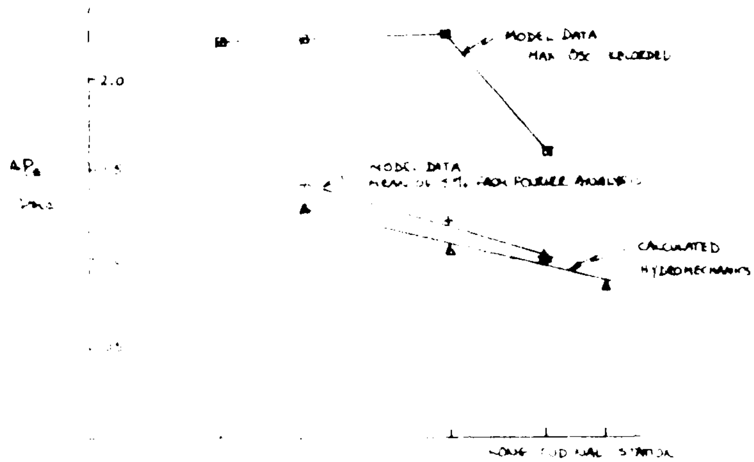
55. Takekuma, K., "Vibration Problems of [illegible] and the Solution from Fitting a [illegible] Symposium on Propeller [illegible] Ship Vibration, RINA, Dec. 1979.

Paul Kaplan, Member

This paper provides an interesting saga about the consequences of unwanted propeller cavitation, as well as the procedures used to establish a successful correction of the associated problems. Although there are a number of items in the paper that can be discussed, my discussion will focus primarily on the analytical prediction of hull pressures and the comparison between theory and experiment. The comparisons are shown in Appendix 2 of the paper, with the implied result that the present theoretical methods provide results that significantly differ from experimental values. Considering only the results of theoretical calculations provided by Hydromechanics, Inc., I can make a number of comments relative to this comparison.

As a general comment I want to object to the nature of the comparison between theory and experiment [illegible] as shown in Fig. 39. The theoretical methods [illegible] of the blade rate amplitudes corresponding to a single frequency, which is obtained by a direct mathematical [illegible] that is analogous to the use of a perfect filter. These [illegible] should not be compared with the maximum value of the experimental pressure signal read from an oscilloscope, which [illegible] include effects due to time variations of the actual wake that are not considered in the theory. A pertinent [illegible] experimental values for comparison purposes should be [illegible] the mean of the highest 5 percent of the blade rate component as shown in Figs. 16 and 25, since that is the preferred measurement considered appropriate by the test laboratory (SSPA). If that information were used as the experimental data, the comparison in Fig. 39 of the paper would then be shown as in Fig. 43 with this discussion. In that case the degree of agreement between the Hydromechanics theoretical predictions and the experimental values of hull pressures would be quite close. The degree of correlation would then be similar to that found in other applications of this theory, as exhibited in [50], which is the basic description of our method. Thus we at Hydromechanics believe that the capabilities for theoretical prediction of pressures due to cavitating propellers are not as dismal as portrayed in this paper.

[2] Nagasaki Technical Institute, Mitsubishi Heavy Industries, Nagasaki, Japan.



[illegible] sures AO 177 [illegible]

[illegible] after reading the excellent paper prepared by the authors which represents the first comprehensive report on the AO 177 [illegible] to consider several questions still remain unan[swered].

[illegible] start off with a provocative statement to enliven the d[iscussion], it appears that the AO 177 design process suffered from [illegible] at the outset. While the authors have de[illegible] the numerous design studies and considerations that [illegible] decisions that led to the unique propeller design, the [illegible] parameters outlined in Table 1 such as speed, length, [illegible] deadweight and block coefficient do not appear [illegible] the state of the art when the AO 177 was designed. [Table] [illegible] with this discussion has been prepared comparing the AO 177 with three merchant ship designs each having highly [skewed] propellers.

[illegible] what this table shows is that these merchant ship [illegible] have equal or greater speed, displacement, shaft [illegible] than the AO 177. The AO 177 propeller is [illegible] the smallest of the group and is by far the lightest [illegible]

[illegible] comparison it would therefore appear since [illegible] 20 K [illegible] merchant ships had been de[signed] [illegible] in operation well in excess of 24 000 shp with [illegible] propellers prior to the AO 177 ship design [illegible] was given to the AO 177 predicted [illegible] without applying sound engineering judg[ment] [illegible] to the questionable accuracy of the propeller [illegible] compatability studies. Emphasis must be given [illegible] to the term *propel[ler]* [illegible] studies.

[illegible] given in the paper to depart from proven [illegible] and select a [illegible] bladed propeller is not [illegible] Actually much of the evidence presented in the [illegible] extremely irregular wake but yet little or [illegible] model tests or hull changes to correct this [illegible] Therefore while the original highly skewed pro[peller] appears to have borne the brunt of the attention [illegible] is the poor stern hull form which caused the [irre]gular wake in the first place and questionable pro[peller] [illegible] studies which in turn resulted [illegible] bladed propeller that provides higher blade fre[quency] components and harmonics from a noise and vibration [stand]point.

[Di]gressing somewhat to comment on other vessels, it should

Table 14 Ship and propeller characteristics

	[illegible]	[illegible]	[illegible]
LBP, ft	[illegible]	[illegible]	[illegible]
Displacement, LT	[illegible]	[illegible]	[illegible]
Speed, knots	[illegible]	[illegible]	[illegible]
SHP	[illegible]	[illegible]	[illegible]
Diameter, ft	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible] blades	[illegible]	[illegible]	[illegible]
Type	[illegible]	[illegible]	[illegible]

be noted that within the past 12 months two other ship designs have suffered propeller/hull/machinery related problems. One high powered containership design analyzed by the most knowledgeable experts was predicted to have excessive stern lateral vibration. On sea trials however, the vessel was found to perform very well from a vibration standpoint, but instead Murphy's Law took effect and what was not predicted happened: all propeller blades bent uniformly ten inches during the [illegible] astern test, resulting in a vessel operating rpm/speed restriction in [illegible] waters until the overall problem is resolved. A second example concerns a bulk carrier design where the propeller was found to overload the main diesel propulsion engines, necessitating cropping 18 in. from the blade tips to achieve a more proper hull/machinery match. The point to be made again is that the design process for propeller/hull/machinery compatibility is not an exact science and there is no substitute for good engineering judgement.

In conclusion, it is apparent that considerable effort went into the highly skewed propeller design and analysis of propeller generated forces. Was equal attention given, however, to [illegible] to the hull form? Also, did the predicted 30 [illegible] longitudinal machinery resonance at full power show itself [illegible] sea trials? In other words, if the authors had a second chance [illegible] again, what changes would be made on the AO 177 propeller/hull/machinery/overall vessel design if follow-on ships were to be constructed? After all is said and done, the fin installation represents the least cost remedial choice to correct a problem generated by a poor hull form.

Edward F. Noonan, Member

The paper represents a great deal of effort by a significant number of individual investigators and an impressive array of [illegible] talent and facilities. It provides a wealth of information, but most importantly it emphasizes the need for a number of significant steps that should be undertaken as a follow-up if we are to improve our ability to profit by our experience in the field of vibration and noise control.

In the first place, I would suggest we associate the problem with the cause, propeller excited forces and moments, rather than with the effect, the airborne noise. Indeed no attempt to attack the problem by classical noise reduction methods was considered, but rather all efforts were properly directed at the identification and reduction of the alternating forces generated by the propeller. As a first suggestion I would have liked to have seen a complete spectral analysis of the hull and compartment vibration and hull pressure forces, with and without the fin, for correlation with the noise data. Of particular importance would be the harmonic content associated with the cavitating seven bladed propeller and the structural response characteristics in the various compartments in which the noise was a factor. Past experience has indicated such airborne noise levels have been significantly reduced by the reduction of cavitation and hull vibration in the range of the higher harmonics of blade rate. [illegible] blade rate levels were acceptable at [illegible] blade rate vibration was noted. [illegible] result of the [illegible] the AO 1[illegible].

My second comment relates to the [illegible] forces in the [illegible] necessary to evaluate these forces [illegible] ensure satisfactory performance [illegible] posed design [illegible] Propeller bearing forces are generally [illegible] reasonably [illegible] augmented [illegible] problem. However, the work [illegible] SSPA points to the possibility [illegible] proposed [illegible] required.

My third comment relates [illegible] of propulsion systems, including the empirical service factors and the [illegible] MIL-STD-167. It is my opinion that the [illegible] is unnecessarily restrictive, and indeed may be incompatible with MIL-STD-167 reduction gear requirements. This same problem has appeared on several other [illegible] attention to both the service factor and MIL-STD-167 requirements.

In 1975, about the same time the AO 177 design was started, the 120 000 m³ LNG carrier, a single screw, 45 000 shp, 20 knot ship built for El Paso Gas Company by Chantiers De France, Dunkerque, was successfully tested and reported on at the Ship Structure Symposium [illegible] the development of this design, SSPA model tests of propeller cavitation indicated the inception of cavitation at approximately 100 rpm. Full scale studies monitored by [illegible] DnV indicated the inception of cavitation actually occurred at 80 rpm. This is a significant variation [illegible] propeller in the wake and was discussed by Hylarides of NSMB at the Ship Vibration Symposium in 1978. I would like to ask the authors to comment on the [illegible] correlation of SSPA model tests with full scale studies such as conducted on the AO 177. How reliable are the model tests in predicting the inception of cavitation on ships in this horsepower range?

On a more general note, this study emphasizes the need for a rational design procedure for use in preliminary ship design to minimize vibration and noise. The 1978 Ship Vibration Symposium, sponsored by the Ship Structures Committee and SNAME, paid particular attention to the subject of vibration and noise aboard ship, and the HS-7 Panel derived the Ship Vibration and Noise Guidelines published in the T&R Bulletin 2-25 in 1980. A "Proposed Five Year Ship Vibration Research Program," based on the 1979 SSC-292 Report "Report on Ship Vibration Symposium" by E. Scott Dillon, was submitted to the Ship Research Committee of the National Research Council by members of Panel HS-7 and was endorsed by the Ship

Structures Committee [illegible] Ship Structures Committee of the National Research Council placed the "Guide for Shipboard Vibration Control" as their number two priority for the current fiscal year. The authors are to be congratulated for their efforts and we [illegible] to be learned from this study [illegible] in the development of a [illegible]

Fred Stern, Member

The problems encountered [illegible] example of the need [illegible] loadings (unsteady [illegible] or forces) so that excessive [illegible] signs. In their detailed description [illegible] the extensive corrective [illegible] a considerable amount of data [illegible] computational [illegible] which [illegible] cavitation [illegible] The extensiveness of the [illegible] The model-scale experiments [illegible] in such a manner that the effects of [illegible] tions and the different wake [illegible] appendages [illegible] be evaluated separately, thereby [illegible] the possibility of designing propellers and [illegible] cavitation and its often deleterious consequences. The good agreement shown between the [illegible] model-scale experiments indicates the usefulness of model-scale [illegible] data in obtaining this goal. [illegible] model [illegible] experimental difficulties [illegible] wall [illegible] sentation and lack of Reynolds number [illegible] Accurate computat[illegible] be reached. Various [illegible] were implemented to predict the propeller blade cavitation and hull pressures and surface forces on the AO-177. Some of the results are given in Appendix 2. [illegible] it is difficult to draw many [illegible] the [illegible] of computational data presented and in this regard I believe the paper would have benefited if more attention had been given to the computational results.

I have also performed calculations for the AO-177 propeller blade cavitation and hull pressures and would like to present some of the results here for comparison with the other calculations shown in Appendix 2. The complete results including detailed comparisons between the predicted cavitation and the model and full-scale experiments were recently reported at the 1982 ONR Symposium on Naval Hydrodynamics [77]. The method employs a dynamical approach in which the form of the instantaneous cavity surface is modeled at each propeller cross section as a semi-ellipse. Values for the cavity length (major axis), thickness (semiminor axis), and position along the section chord are determined such that the nonlinear cavity surface boundary conditions are satisfied approximately. The pressure on the instantaneous cavity surface is obtained using a two-dimensional, thick-section, unsteady potential flow computer program. Three-dimensional propeller effects are included by correcting the harmonics of the vertical component of the section inflow using the results from an unsteady propeller lifting-line computer program. The vertical component of the section inflow is obtained from the nominal wake modified to represent an effective wake using data for axisymmetric bodies.

Figures 44 and 45 herewith show the predicted cavity volume and volume velocity. The results show substantial reductions due to the addition of the flow modifying fin. The reductions are due principally to a decrease in the cavity thickness as was also found in both the model and full-scale experiments. The cavity volume velocity (Fig. 45) has been harmonically analyzed (see Fig. 46) and the free-space pressures calculated (see Fig. 47) for comparison with the other calculations and ex-

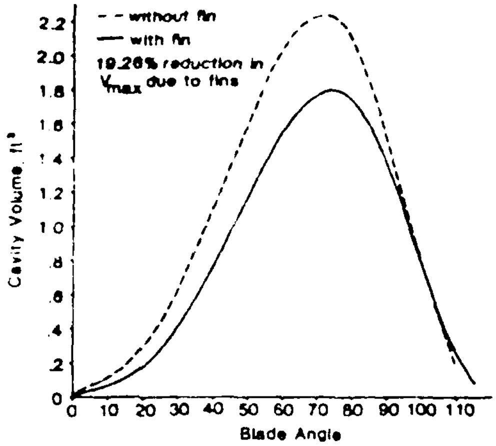


Fig. 44 Cavity volume prediction for the AO-177 propeller

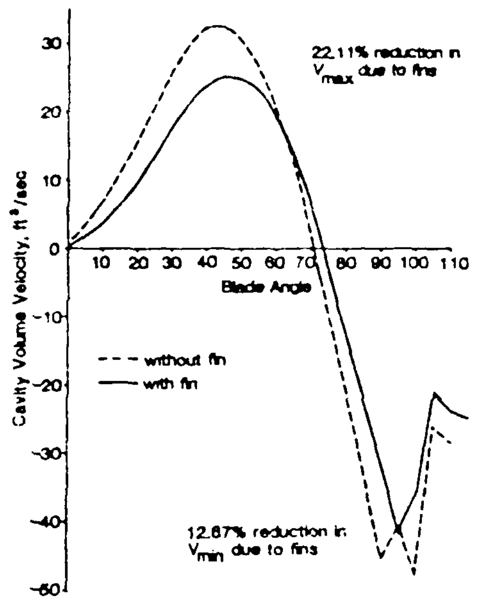


Fig. 45 Cavity volume velocity prediction for the AO-177 propeller

perimental data shown in Fig. 39 (in the paper). A value of 2 was used for the reflection coefficient in the free-space pressure calculation. This approximate procedure for calculating hull pressures due to unsteady cavitation is in common use and, in fact, was also used by HI and DnV. The results are seen from Fig. 46 to be below the model and full-scale experimental data. The results do show the same trend as the experiments with regard to the effects of the fins, that is, a reduction in the pressure magnitude except for directly over the tip where the effects of reduced tip clearance offset the reduction due to the fin in the seventh harmonic of the cavity volume velocity, $\dot{V}_7$. The "free space factor of two" method is correct for the limit of an infinite flat plate [illegible] infinitely long cylinder. This

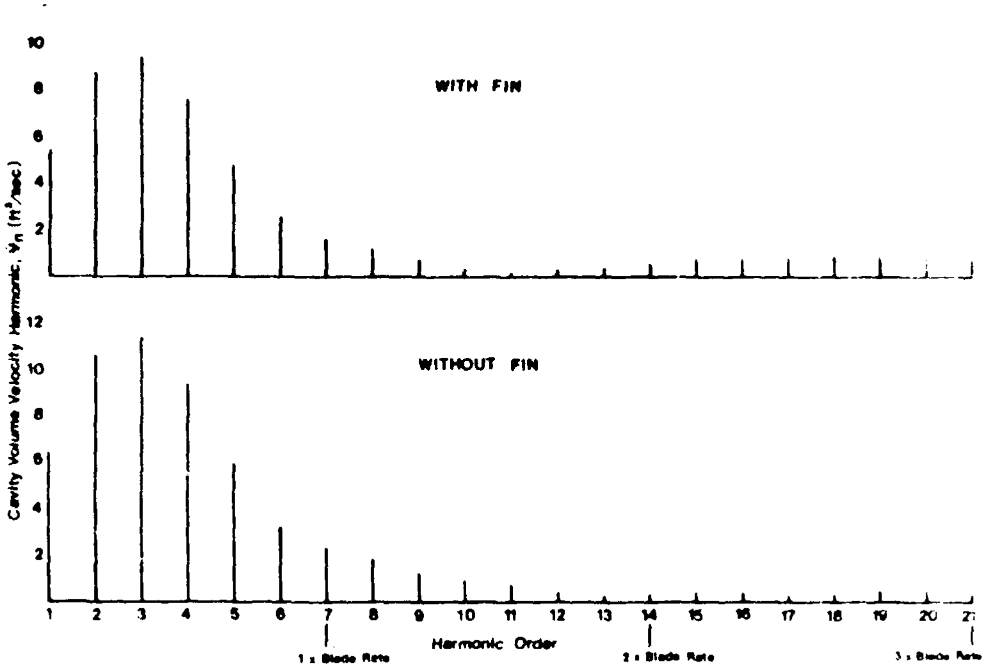


Fig. 46 Cavity volume velocity harmonics for the AO-[illegible] propeller

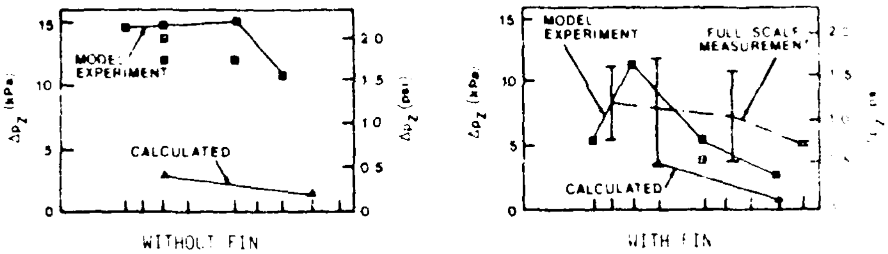


Fig. 47 Comparison of blade rate pressure amplitudes with experiments

neglects the water free surface pressure relief effects and accurate representation of hull reflection effects. The former effect reduces the pressure magnitude. The latter effect may increase or decrease the pressure magnitude depending on the specific hull geometry. A comparison of Fig. 47 with Fig. 39 (in the paper) shows that the present results give larger magnitudes than the more sophisticated methods of VAI and SIT. This is most likely due to large water free-surface pressure relief effects. However, this is not substantiated by the experimental data. The good agreement between model-scale results obtained using a rigid wall water free-surface and the full-scale results implies small water free-surface pressure relief effects. The VAI and SIT results also show an increase in hull pressures due to the fin which seems improbable. In order to draw more conclusions it would be necessary to make a comparison between the cavity volume and volume velocity variations predicted experimentally and by the various computational methods. Such a comparison is important due to the dominating effects of cavitation on hull pressures. It is hoped, with regard to this matter, that the experimental difficulties in measuring cavity volumes and volume [illegible] overcome since these data are imperative [illegible] validating the cavity prediction [illegible]

I believe that the computational results [illegible] though, clearly, as stated by the authors [illegible] developments and improvements. These [illegible] particularly at the early design stage [illegible] of many design options can be evaluated.

Additional reference

57 Stern, F., "Comparison of Computational [illegible] Unsteady Cavitation," presented at the [illegible] Arbor, Mich., Aug. 1982.

Jacques B. Hadler, Member

It was a pleasure to receive this paper at [illegible] involved in a number of propeller designs [illegible] a ship that has a wake pattern with almost [illegible] gradient and wake defect at top dead center [illegible] modified AO-177.

In general, I agree with the authors' conclusions on the propeller blade characteristics which seem to be most successful for reducing the likelihood of cavitation erosion, trailing edge bending and minimal higher harmonics of blade frequency with acceptable blade frequency forces. I have used the technique, whenever I have had to design a propeller for such a ship, of designing three or four propellers in which I have made small but systematic variations in either radial load distribution at the tip, variations in plan form or the amount of camber in the tip sections. A model propeller is then constructed with each blade to a different one of the designs. The propeller is then tested in the variable pressure water tunnel behind wake screens or partial hull bodies combined with wake screens which simulate the wake measured on the ship model. These tests, which can approximate both the load and ballast condition of operation, show the extent of growth and decay of the sheet and tip vortex cavitation as the blades pass through the low velocity region. Through strobe lighting, it is easy to compare one blade with the others in directly comparable flow conditions and find the blade which produces the most stable cavity that collapses in the tip vortex of the blade. The results of this approach have always lead me to the following conclusions.

(a) Radial blade loading distributions which approached the Lerb's optimum were best.

(b) The amount of camber at the blade tips should be limited so the sections are not hollow on the pressure face.

(c) Plan forms which produced pointed tips even at the trailing edge were not successful.

(d) Wide tips are generally better than narrow, although there is some evidence that there is a "best" length.

These propellers have had varying amounts of skew up to a maximum of about 30 deg. So far, all propellers developed by this approach have been successful.

I agree with the overall approach used by the authors in the new five bladed design except for the shape of the trailing edge at the tip, which is more "pointed" than I have found successful.

I am quite surprised at the author's estimate that the periodic thrust at the thrust bearing may be 27 times that calculated by unsteady lifting surface theory using model wake data. I agree and have witnessed on vibration trials a modulation that may approach three when there is a large amount of turbulence in the wake due to flow separation, but a factor of three is excessive in my experience for free-surface effects and for turns. The most that I have ever noted is a factor of two on twin-screw ships in a tight turn and less than 1.5 for free-surface effects. Could the authors cite their evidence for such large factors?

In closing, I cannot help but note that it almost always seems to take a design failure to precipitate a major technical investigation which can extend our fountain of knowledge. We are fortunate that the authors could share this knowledge with us.

David W. Byers, Member

The views expressed herein are the opinions of the discusser and not necessarily those of the Department of Defense or the Department of the Navy.

The authors have presented a comprehensive treatment of how a propeller-excited noise problem discovered during sea trials of the AO-177 was ultimately resolved. This problem arose as a result of incomplete understanding of hull-propulsor interactions on the AO-177 while under design from 1972 to 1974. I would like to briefly address the question: How are we in the U.S. Navy design community at NAVSEA ensuring that such a problem does not recur on future designs?

First of all, in the area of hull form design, we are smarter today than we were [illegible] years ago. As suggested in the authors' references 2 and 25, the [illegible] afterbody design in way of the propeller of an AO-177 designed today would clearly be more bulbous in character and have greater [illegible] way of the hull below the propeller shaft.

More importantly, the [illegible] need to validate performance predictions of the hull propulsor system with a sufficiently large scale propeller model tested in the behind the ship condition at a facility capable of accurately modeling the wake field has been recognized. Pending refinement of the various analytic techniques for predicting hull pressure [illegible] which are presented in Appendix 2 of the paper, such tests are now considered a standard component of model test programs for fleet auxiliaries. Subsequent to the AO-177 tests discussed in the paper, NAVSEA and [illegible] David W. Taylor Naval Ship Research and Development Center (DTNSRDC) undertook a similar cavitation test program [illegible] nozzle propulsor system on the ARS-50 salvage ship design at SSPA and are planning comparable programs [illegible] AO [illegible] oiler and AOE-6 fast combat support ship currently under design.

Testing at a foreign facility such as SSPA is necessary since no comparable facility presently exists in the United States. To rectify this deficiency, current plans call for construction at DTNSRDC beginning in Fiscal Year 1985 of a large cavitation channel with a 10-ft by 10-ft by 45-ft long test section, speed capability of 50 fps at a pressure [illegible]. Until this facility is operational in Fiscal Year 1989, NAVSEA will continue to rely on cavitation tanks such as SSPA for hull propulsor system tests of auxiliaries. [illegible] the expected improvements in analytic techniques, such tests should minimize the chances of a recurrence of cavitation-related problems such as those which [illegible] the AO-177.

Stephen G. Arntson, [illegible] Visitor, **K. [illegible],** Visitor, and **Michael Lusick,** Visitor

The views expressed herein are the opinions of the [illegible] and not necessarily those of the Department of Defense or the Department of the Navy.

The authors have presented an interesting and informative paper. They have discussed why the flow accelerating fin was installed. It may be of some interest to describe how the fin was installed.

The fin installation was beset with a number of major problems, the biggest of which was [illegible]. The decision to install the fin was approved around December 1980 with the proviso that the task be completed by early May 1981—just five months! Backing down from the completion date to allow for installation in dry dock, prefabrication, ordering of materials and letting an overhaul contract, this meant the detail design had to be ready by mid February 1981. The schedule did not allow for slippage at any point.

A second major problem involved the number of participants involved. Avondale Shipyards Inc. (ASI), tasked through the Supervisor of Shipbuilding, New Orleans, developed the detailed drawings including lofting since ASI was the builder of the AO-177 and had four more AO-177 class ships under contract. However, ASI could not install the first fin as the AO-177 had already deployed to the West Coast. The AO-177 fin installation could possibly have been done by any of a number of yards from Seattle to San Diego. Subsequently, Todd Shipyard's Alameda, California facility got the contract and worked under the direction of the Supervisor of Shipbuilding, San Francisco. The second ship of the class, the AO-178, having already been delivered, would have her fin

[1] Naval Sea Systems Command, Washington, D.C.

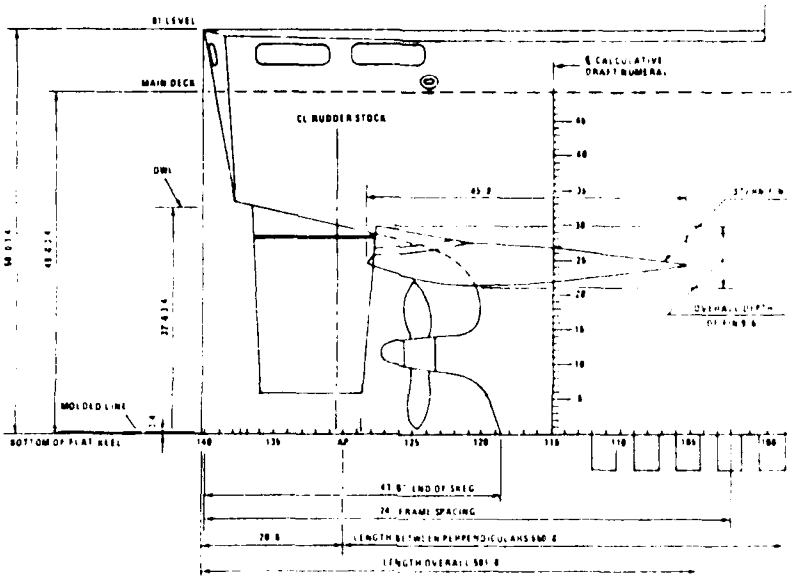


Fig. 48 AO-177 outboard profile aft showing fin

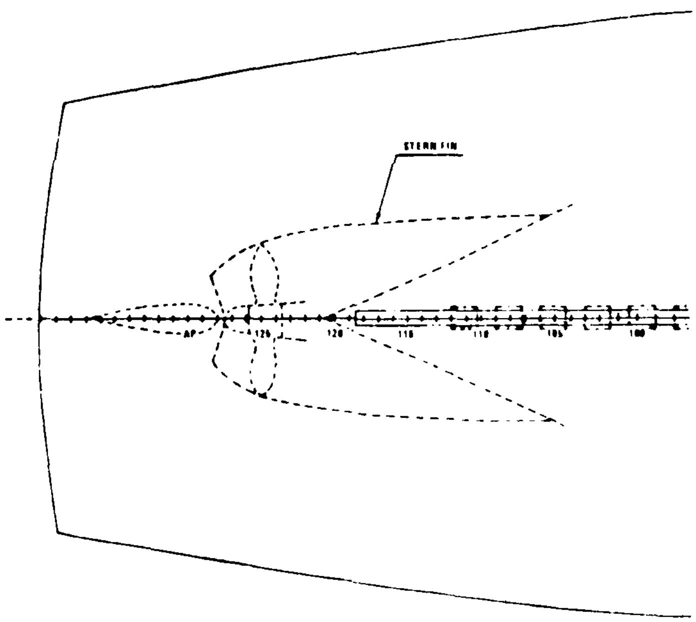


Fig. 49 AO-177 plan views aft showing fin

installed by the Naval Shipyard at Charleston, South Carolina. The fins for the remaining ships would be installed by the shipbuilder, ASI. All in all, there were two commercial yards, one naval shipyard and two SUPSHIP offices involved in addition to many codes within NAVSEA.

Considering the tight schedule and likelihood of a "too many cooks" phenomenon, it is pleasantly surprising that things went as smoothly as they did. This was due mainly to the exceptionally cooperative effort put forth by all concerned.

As can be seen from the figures, the fin is rather large. The overall depth of the structure was 9 ft 6 in., with a width of about 18 ft 6 in., and an overall length of 45 ft 9 in. The thickness of the fin is sufficient to allow quite adequate access to the interior for welding, painting, inspection, etc. The complex shape of the fin can be seen in Figs. 48-50 herewith.

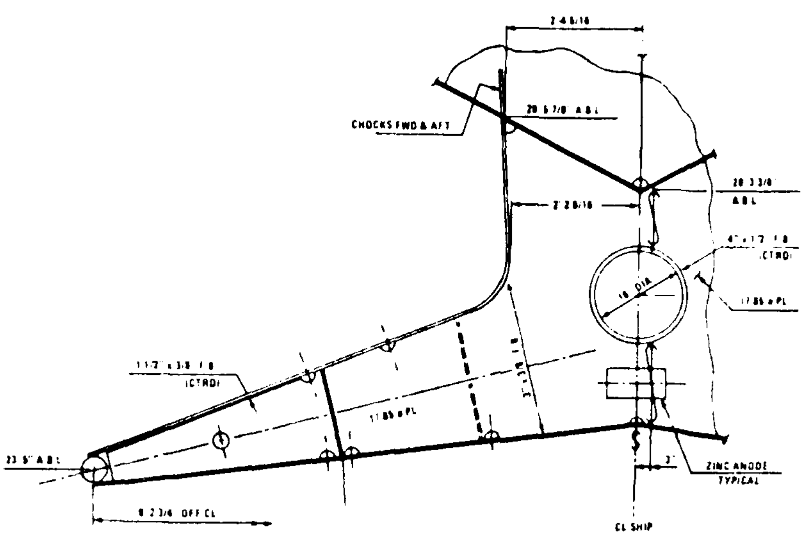


Fig. 50 Section view of fin AO-177

The structural design of the fin was fairly straightforward although several issues evolved to complicate it. The first cut at the scantlings maintained the general plate thicknesses and arrangement of adjacent hull structure and was transversely framed with webs at 24-in. spacing. Analysis of the resulting structure indicated it would withstand a general slam ("beaver tail slap") to at least 12 000 psf. Since standard practice would have predicted loads of only 1000 psf, these "minimum" scantlings were maintained. Plating was commercial grade MS except for the lower face in way of the propeller, which was Navy grade HY-80 to protect against erosion. Actually, HY-100 was used for the AO 177 when sufficient amounts of HY-80 could not be acquired within the time available.

An unusual feature of the fin is that it is free flooding. In order not to have an adverse effect on the trim of the ship (down by the head under certain load conditions), it was determined early on that the fin could not just be an empty void. Various concepts for locked-in liquid ballast were considered but rejected because of problems of freezing (the fin is often at or above the waterline), chemical contamination and penetrations of the hull in case the installation was not hydrodynamically successful and was later removed. Thus it evolved that the greater part of the fin (any section over 18 in. in depth) would be free flooding. Flood holes were provided on the under surface and vent holes above, *just like a submarine*. The interior was protected by coatings and zinc anodes. Access plates are provided for inspection and maintenance of the interior of the fin.

The only problem unresolved after the initial installation involved the adequacy of the propeller shipping pad eyes (flush type) installed on the underside of the fin. This was resolved by a design modification on subsequent installation by the addition of another pair of pad eyes.

In an age when it is easy to be cynical about the Navy's ability to work with industry to respond quickly and effectively, it was refreshing to be involved in a project which was as successful as this one. The authors and the major facilities involved are to be congratulated.

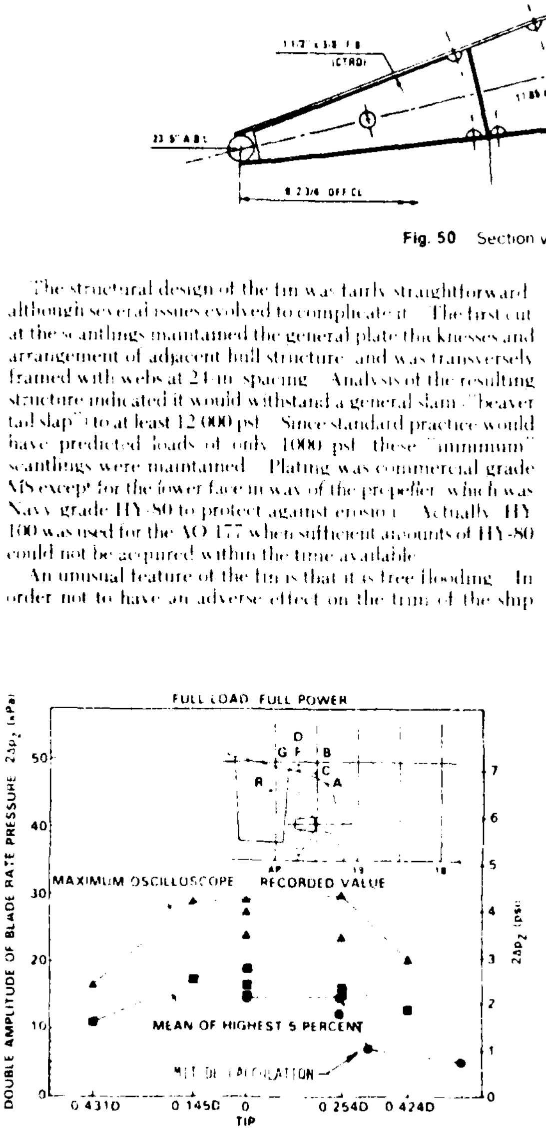


Fig. 51 Figure 16 of paper with MIT-Davidson Laboratory calculated values superposed for AO-177 without fin

J. P. Breslin, Member, and **T. G. McKee**,[14] Visitor

Propeller induced pressures on the afterbody of the AO 177 without fin have recently (16 November 1982) been computed as a part of the documentation of the MIT-DL propeller-hull program described in the Breslin et al paper given earlier in this volume. Comparisons of the pressures at five points as measured and reported in Fig. 16 of the present paper with those calculated are shown in Fig. 51 of this discussion. Here we compare our calculated double amplitude (for the rigid condition on the water surface) with the mean of the 5 percent highest values measured on the model at SSPA. This is the level used by SSPA for predictive purposes as explained earlier in the Breslin et al paper.

[14] Davidson Laboratory, Stevens Institute of Technology, Hoboken, N.J.

It is seen that the correlation is excellent near to the propeller, but beyond 0.25D the calculated values are about half of those from measurement.

As the theory does not include temporal variations of the flow and, hence, no statistical variations in pressure amplitude (or phase), it is reasonable to question the significance of correlation with a particular part of the nonstationary model test output. The agreement might be considered as fortuitous, *but of highly practical value since the twelve-year experience at SSPA shows that their means of the 5 percent highest amplitudes correlates well with full-scale results.*

Clearly, the predictions made via an ad-hoc theory developed hurriedly at Davidson Laboratory compare poorly with the maximum amplitudes in the authors' Fig. 39 for the finless case. A decision to represent the cavity potential by only three terms (which dominate the far field) is now seen to be a poor approximation in the near field. A more effective ad-hoc model is believed to be that developed in the discussion of the Huse/Guogiang paper by Breslin, which appears earlier in this volume.

In any event, the calculation of hull pressures arising from intermittent cavitation must be regarded as still in its formative period. We must expect that theoretical conceptions, which include the physics of the phenomenon, will give far more consistent results than the ad-hoc formulations.

Schelte Hylarides,[15] Visitor

This paper contains a great amount of practical design aspects on vibration problems aboard ships as generated by the propeller. Their use—the pros and cons—the considerations as to which choice should be made between the various possibilities, are dealt with very extensively. Also is illustrated the fact that many questions are still open, so that very often the designer has to operate on intuition. I therefore think that we unanimously agree in complimenting the authors for their valuable work.

In spite of the rather extensive description, it is not clear to me why finally the flow-accelerating fin with the original propeller was selected. *In my opinion we can state the problem* as follows:

- the vibration level is acceptable,
- the noise level is by far too high, and
- the cause is the intermittent propeller cavitation.

Knowing this, the alterations on ship or propeller should be aimed at reducing the higher harmonics of the hull pressure fluctuations.

Looking to Fig. 25 of the paper, one directly concludes that for the higher harmonics the tunnel fin is by far more effective than the flow-accelerating fin. Although not mentioned in the text, I expect that Propeller A (the five-bladed, wide-blade propeller) is also very effective in reducing the higher harmonics. This opinion is based on the large effect of Propeller A on the pulses with blade harmonic frequency (Table 9, Fig. 24) and on the complete redesign of the propeller that has been performed. So the obvious solutions would be:

(*a*) the tunnel-fin, or

(*b*) the 5-bladed newly designed propeller.

Yet the flow-accelerating fin has been selected.

According to the paper the flow-accelerating fin was selected because, according to the SSPA vibration criterion, for this fin the pressure limit is the highest. The authors start the justification of their choice with the words: "If it is assumed that the SSPA vibration criterion has general applicability. . . ." etc. In my opinion this assumption is not correct. This criterion has been based on experiences with ships without fins and therefore cannot be used in a case where the fin is applied.

When applying a fin the pressure field around the propeller tip will have lower amplitudes, but due to the smaller clearance the ship structure is moved into the region with high pressure amplitudes. These two aspects combined result in a different pressure distribution on the structure with respect to amplitude and phase. The integration of this pressure field can lead to lower or higher forces and moments than originally. In case, for example, that with a fin the vertical force F_z is larger than without a fin, one may expect that the vertical vibration level increases proportionally. The increase of hull stiffness due to the fin will have a negligible effect. Further, one can state that larger pressures lead to larger forces, unless the phase distribution is changed so that the pressures balance each other to a certain degree. But then a reduction of the excitation system can only be small.

Therefore at MARIN we state that pressure fluctuations have to be reduced if a fin is used. The decreased vertical clearance surely is no reason to allow a higher pressure level on the fin.

[15] Maritime Research Institute (MARIN), Wageningen, The Netherlands.

Authors' Closure

The authors sincerely thank all of the discussers. Their contributions have greatly enhanced the value of our paper.

We will reply first to points raised regarding the propeller design and propeller performance. Then we will respond to other points including those associated with hull pressures and forces, fin selection, and airborne noise.

Several discussers, including Messrs. Zaloumis, Raestad, Hammer, Noonan, and Professor Hadler commented on the severe requirements regarding maximum allowable blade rate bearing forces that were imposed on the propeller design. Essentially all of these discussers felt that these requirements were too severe. As discussed in the paper, these bearing force requirements influenced the design of the propeller on the AO-177 to a much greater degree than is usual practice. The U.S. Navy requirements and rationale that led to the maximum allowable bearing forces are summarized in the paper and amplified in the discussion by Mr. Zaloumis. We thank Mr. Zaloumis for the supplemental information in his discussion. The rationale for blade rate thrust includes:

1. MIL-STD-167 for allowable vibration level in the propulsion system.
2. Propulsion system vibratory response calculations.
3. Empirical multiplicative factors on the calculated propeller forces to consider the influence of:
   (*a*) modulation,
   (*b*) nonlinear effects at high speed, and
   (*c*) turns.

Mr. Zaloumis described the derivation of the empirical multiplicative factors. His discussion answered some of the questions asked by other discussers, so those points will not be repeated here.

The empirical multiplicative factors inherently include factors of safety for the influence of phenomena that presently cannot be calculated directly, such as:

1. Wake scaling effects (differences in the pertinent harmonics of the nominal wake between model and full scale).
2. Effective wake distribution (influence of the propeller on the pertinent harmonics of the wake).
3. Possible effects of cavitation on periodic propeller loads.
4. Possible effects of the free surface on periodic propeller loads.
5. Inaccuracies (including inaccuracies in model wake experiments, propeller loading calculations, shafting response calculations, bearing support stiffnesses, etc.)

The authors agree with several of the discussers who suggest that the empirical multiplicative factors are overly conservative. Conservative factors of safety are reasonable engineering tools so long as they do not lead to other problems. *Unfortunately*, this did not turn out to be the case on the AO-177. The authors fully endorse Mr. Noonan's suggestion that the empirical multiplicative factors should be carefully reviewed and relaxed as appropriate.

As discussed in the paper, the authors agree with Mr. Raestad that the accuracy of predicting bearing forces as low as 1 percent of the time average thrust is poor. However, it is felt that periodic bearing force calculations do yield a reasonable indication of the relative performance (or ranking) of different candidate propellers (design options). The uncertainty in the calculated periodic bearing forces is considered in the empirical factors of safety as discussed in the preceding paragraph.

We also agree with Mr. Raestad that the bearing forces in turns and straight ahead are essentially unrelated because the wake patterns are completely different for these two cases. However, since wake data are not, in general, available in turns, the maximum bearing forces in turns are empirically estimated to be three times the maximum bearing forces in straight-ahead operations.

Mr. Hammer raised several questions regarding the propeller design. He states that the real villain in this case is the hull which produced the poor wake in which the propeller must operate, and the propeller machinery studies which dictated very small allowable blade rate bearing force components. From the propeller designer's point of view, the authors certainly agree with this assessment. However, from overall ship design viewpoint the story is more complicated.

The hull design for AO-177 was completed eight years ago. It was designed primarily for high propulsive efficiency which could be quantified through model experiments. This was a requirement imposed on the design to maximize range.

It was recognized that this hull produced a severe wake in the propeller plane. However, at the time of the hull design there was no reliable validated technique for predicting propeller-induced hull vibration and airborne noise, certainly none that was applicable to a highly skewed propeller, or to a seven-bladed propeller. However, it was judged that the combination of high skew and generous tip clearance (30 percent of diameter) on the AO-177 would minimize the likelihood of these problems. In fact, the AO-177 as built without fin was satisfactory from the vibration point of view, but suffered from excessive noise. It remains the opinion of the authors that if the ship had an unskewed propeller with the same number of blades and identical other parameters then the levels of vibration and noise would be much higher than was experienced on the AO-177 with the skewed propeller. In any event, the hull designers selected a known gain in propulsive efficiency over reducing an unknown risk of problems associated with hull vibration or noise.

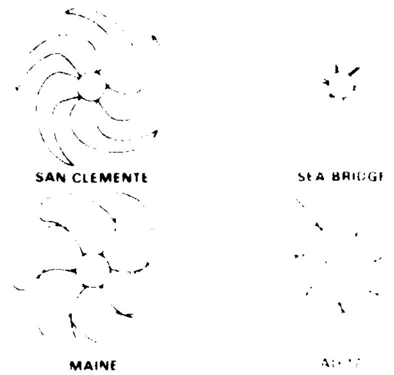


Fig. 52 Comparative skewed propellers

Mr. Hammer cited three highly successful skewed propellers applied to merchant ships. These propellers and the AO-177 propeller are shown in Fig. 52 with this closure. All of these merchant ship propellers were designed by DTNSRDC using essentially the same techniques and philosophies as was used for the AO-177 propeller design. However, the wake nonuniformity and bearing force requirements are more severe for the AO-177. These propellers exhibit a wide variety of geometries based on fine tuning of the propellers to the particular wake and design requirements. The primary departure of the AO-177 propeller from these designs was the use of seven blades and a smaller diameter. Seven blades did not directly lead to problems on the AO-177, rather the short chords near the tips which are a by-product of the high number of blades and the requirement to avoid a pointed trailing edge near the tip contributed to the airborne noise problem.

Table 15 herewith compares the blade frequency bearing

Table 15 Blade rate bearing forces on comparative skewed propellers

	AO 177 LIMITS	AO 177 EXISTING PROPELLER	AO 177 PRELIMINARY REDESIGN PROPELLER	SEA BRIDGE	MAINE	AO 177 REDESIGN PROPELLER	SAN CLEMENTE
NUMBER OF BLADES	7	7	6	6	6	5	5
SKEW AT TIP (DEGREES)	46	46	46	60	30	30	72
100X BLADE RATE THRUST / STEADY THRUST	1.0	0.9	0.9	2.4	1.2	2.9	0.5
100X BLADE RATE VERTICAL FORCE / STEADY THRUST	0.7	0.3	1.1	0.4	1.6	1.3	0.4
100X BLADE RATE TRANSVERSE FORCE / STEADY THRUST	0.7	0.1	1.3	0.7	0.6	2.8	0.8

ALL VALUES CALCULATED BY METHOD OF TSAKONAS ET AL[8] USING MODEL NOMINAL WAKE DISTRIBUTIONS WITHOUT EFFECT OF CAVITATION

force requirements for the AO 177 with the calculated blade frequency bearing forces on the AO 177 propeller, on the three cases cited by Mr. Hammer in their respective design wakes, and on five- and six-bladed propeller design options for the AO 177. All calculated values are based on the procedures used for the AO 177 propeller design as discussed in the paper. Table 15 shows that none of the propellers except the seven-bladed AO 177 propeller meets the bearing force requirements imposed on the AO 177 propeller design. This illustrates that the severe bearing force requirements drove the design of the AO 177 propeller.

Mr. Hammer asked what would we do differently if we were designing the AO 177 today with benefit of today's knowledge. Basically, we would do three things differently:

1. Design the hull with a bulbous stern, as discussed by Mr. Byers, to produce a more uniform wake in the propeller plane. Alternatively, use an open stern hull design typical of many existing U.S. Navy auxiliary and combatant ships whose main hull wakes are very mild.

2. Make a different tradeoff between a hull design for maximum propulsive efficiency and one designed for reduced risks of vibration, airborne noise, and cavitation erosion.

3. Increase the maximum allowable blade rate bearing force components and design a five-bladed skewed propeller as discussed in the paper.

Mr. Hammer asked whether the predicted resonance in the propulsion system at 10 Hz, which eliminated consideration of a six-bladed propeller, was observed in the trials. As discussed in the paper, the trials indicated that this resonance occurred near 7.5 Hz rather than 10 Hz. This rather poor prediction of resonance frequency is primarily due to inability to adequately predict the stiffness of the bearing support in the design stage.

Professor Hadler stated some of his design experience and model evaluation techniques with us in his discussion. The authors thank him for this. Much of his experience is similar to ours as discussed in the paper.

Professor Hadler and Mr. Bjarne cite a general guideline of low values of camber near the tip for reducing the likelihood of cavitation erosion, bent trailing edges, and minimal harmonics of blade frequency hull forces. This guideline is based primarily on experience with unskewed propellers. However, the relatively high value of camber-to-chord ratio near the tips of the AO 177 propeller is due to short chords rather than high camber. Further, these are significantly influenced by lifting surface corrections due to skew, so typical values applicable to unskewed propellers are not necessarily applicable here.

Professor Hadler recommended avoiding a pointed trailing edge profile near the tips. Pointed trailing edge profiles near the tips were unavoidable on both the original and redesign propellers on the AO 177 due to the severe bearing force criteria. Further, the three skewed propeller designs discussed by Mr. Hammer (see Fig. 52) had pointed trailing edge profiles near the tips without significant cavitation erosion, propeller-induced vibration, or propeller-induced airborne noise.

Mr. Takekuma correctly commented that the diameter of the AO 177 propeller is less than the diameter for optimum propulsive efficiency. The diameter for optimum propulsive efficiency, 7.0 m (23 ft), and the corresponding optimum rotational speed, 100 rpm, were selected during the preliminary design stage; however, the diameter was reduced to 6.4 m (21 ft) during the detailed design stage to meet the bearing force criteria. Calculations indicated that the smaller diameter would cause insignificant loss in propulsive efficiency and the smaller diameter resulted in a lighter propeller with larger tip clearance. The reduction gearing was fixed when the diameter was reduced, so the rpm could not be increased to its optimum value for a 6.4 m (21 ft) diameter. However, calculations showed that propulsive efficiency is insensitive to change in design rotational speed from 100 rpm to 120 rpm.

Mr. Takekuma suggested higher values of propeller expanded area ratio than that used for the AO 177 propeller. The blade chord lengths at each radius on the AO 177 propeller were determined by analysis based upon blade section cavitation buckets. The resulting expanded area ratio A_E/A_0 was checked against minimum criteria of Burrill and Emerson (58) for freedom from thrust breakdown and of Lindgren and Bjarne (18) for freedom from excessive cavitation erosion. However, Propeller A evaluated at SSPA and the proposed redesign propeller had wider blades near the tips resulting in higher values of A_E/A_0. The values of A_E/A_0 are as follows:

Propeller	A_E/A_0
AO 177	0.73
Propeller A	0.82
Proposed redesign for AO 177	0.82
Value suggested by Mr. Takekuma	0.8[illegible]

Wider blades may help alleviate the problems that occurred on the AO 177; however, care must be exercised to avoid excessive blade width because increasing blade width causes increased weight, increased cost, and reduced propulsive efficiency due to increased viscous drag.

We turn now to discussion points relating to the propeller-induced excitation pressures, ship response and inboard noise, and the alternative fin designs.

Mr. Bjarne and Mr. Noonan expressed interest in information concerning the hull girder vibration and the localized vibration in the troublesome compartments of the ship. Of course we agree such data would be useful and complementary information. However, extensive local compartment vibration data do not exist, and unfortunately the hull girder vibration data for this Navy ship are restricted. Nevertheless, it may be noted that the crucial vibration components measured at the usual representative locations such as the vertical amplitudes at fantail centerline on the main deck and the horizontal amplitudes at the top of the deckhouse were found to be acceptable in terms of both the U.S. Navy standard and the ranges recommended by the International Standards Organization (see, for example, reference 16). Therefore, the girder vibration levels are not considered to be excessive.

Mr. Bjarne's recommendation that the mean values of the third blade rate harmonic of the measured model scale pressure pulse amplitudes be used for best correlation with the observed changes in very low frequency full scale interior noise is interesting. We believe that a reliable empirical trend for judging an interior noise correlation should be established using numerous examples, not just this one case. We may observe that there are very few published studies involving interior noise excited by the propeller. We have concentrated on judging the probable merits of our various corrective options based on the relative levels of the pressure pulse amplitudes.

In answer to Mr. Bjarne's suggestion about the possible source of interior noise, we believe that it is unlikely that there are sufficient loose bulkheads, detached stringers, etc., to explain the widespread occurrence of inboard airborne noise on the AO 177 as *rattling* response to low frequency vibration.

We are further indebted to Mr. Bjarne for his data on the large pressure pulse amplitudes that may accompany propeller hull vortex cavitation for a propeller in a duct.

Mr. Raestad inquired whether the characteristics of expected superstructure vibration influenced the choice of number of blades. There were numerous check calculations performed on the natural frequencies of typical panels and substructures located throughout the stern of the ship, but estimated super-

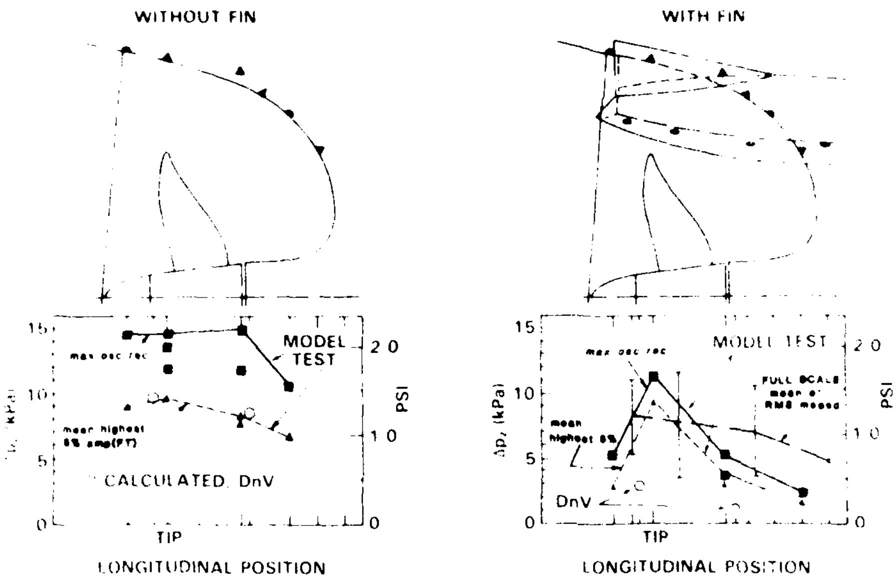


Fig. 53 Comparison of measured blade rate pressure pulse amplitudes with computed values from DnV

structure resonant frequencies were not directly considered in the propeller design. Previous Navy experience has shown that lower numbers of blades, such as four or five, are more likely to [illegible] difficulties along these lines. Two resonant frequencies of the deckhouse were observed during vibration surveys of the unmodified ship. In each case the response was very [illegible] tuned, and even after the vibration levels at the top of the deckhouse were allowed to build up to peak response, the amplitudes were not judged excessive, as explained earlier.

Mr. Raestad noted that calculations of periodic pressure amplitudes were carried out by DnV and reported in reference [illegible] for the AO-177 hull without and with the flow-accelerating fin. These data were not included in Fig. 39 because only two of the points fell within the longitudinal interval covered by [illegible], so the local trend is not clearly defined. However, this omission is corrected with Fig. 53, which shows the DnV computed blade rate pressure amplitude points for each [illegible] and comparison with the model and full scale measurements. Included are curves for two measures of the model [illegible]: (1) the mean of the highest 5 percent amplitudes [illegible] and (2) the maximum oscillograph values. The calculated values fall below the maximum oscillograph recorded values for both without-fin and with-fin cases. For the case of no fin, the agreement between the DnV computed amplitudes and the highest 5 percent curve is excellent.

Mr. Raestad also pointed out that we did not include comparison between patterns of calculated and model observations of extent of cavitation. Although interesting and potentially useful, these comparisons have not been presented because of the length of this paper.

We heartily endorse the idea stated by Mr. Raestad and Dr. Kaplan that there is a distinct need for early stage guidance on the possibility of unsteady cavitating propeller excitation problems that could be provided by analytical prediction schemes such as those described briefly in Appendix 2. At least in the U.S. Navy design community, the experience with the AO-177 has added an impetus to activities started some years ago to upgrade capability and initiate fresh directions for research in this area.

The use of the term "airborne noise" to describe the noise levels detected with a microphone and perceived by the ear in the interior spaces of a ship conforms to U.S. Navy practice. Thus, there is simply a semantical difference between this label and the term structureborne noise mentioned by Mr. Raestad to describe the noise levels (measured in air) transmitted to the compartment by a structural path. Perhaps a better term might be interior noise.

Mr. Takekuma questioned whether it was inconsistent that airborne noise was the dominant problem on this ship while the pressure pulses measured in the model tests showed that the blade rate component of periodic pressure was larger than any of the higher harmonic components. The fact that the interior airborne noise levels instead of hull vibration was the main problem in many after spaces of this ship was simply a matter of measurement and comparison with allowable criteria. We see no reason to suppose that the absolute levels of the higher harmonic pressure pulse components (say those in the range 50 Hz to 250 Hz) need to be larger than the blade rate levels in order to cause excessive interior noise. What is involved here is a complicated transmission process that depends on the frequency-dependent impedance characteristics of the structure and the detailed noise radiation properties of the boundaries of the compartments. Without detailed (and very expensive) acoustoelastic calibration of the ship, all we can say about the particular composition of pressure pulse spectra for the AO-177 is that the higher frequency excitation levels were large enough to cause the problems described.

Mr. Takekuma pointed out that the net improvement of overall ship propulsive performance with the flow accelerating fin installed (compared with the no fin case) seems to hinge on a noticeable increase of the relative rotative efficiency η_R. This applies only to the ballast condition with the hull trimmed 1.14 m (3.75 ft) down by the stern. Changes in the propulsive interaction coefficient η_R are often difficult to understand and

motivate. In this case there are changes in the three velocity component ratios of the nominal wake, comparing the ballast condition with the full load condition, that may explain the improvement in η_H. Within the main wake shadow, the V_X/V values for the ballast condition are increased and wake extent is broadened, so that the tangential gradients are reduced compared with the velocity patterns of the full load condition. Similarly, the peaks of the V_T/V and V_R/V variations versus circumferential angle are reduced for the ballast condition compared with the full load case. Overall then, the velocity circumferential gradients are diminished in the ballast condition wake field, and the somewhat weakened sheared flow pattern could be responsible for the larger η_H trend in that condition.

Mr. Takekuma expressed concern with the wide band of measurements of pressure pulse amplitudes displayed in Fig. 38. This scatter reflects the character of the observed pressure signals. This may in part be attributed to temporal variations that are known to be present, especially in full scale measurements. Although the data shown here exhibit large scatter, which is rather unsettling to us as well as to Mr. Takekuma, there are other examples of measured pressure pulse data that illustrate variability, for instance, the measurements reported by Holden et al. [9]. We should be advised for future measurement work to analyze the data in a stricter statistical manner, where an ensemble mean value is identified, along with the standard deviation and the extent of maximum and minimum values.

Dr. Kaplan's complaint about the use of the measured maximum oscillograph amplitude of fluctuating pressure for the comparison with the analytical results is well taken. For clarity, it should be noted that it is the maximum amplitude of the blade rate filtered signal that has been displayed in these comparisons. Nevertheless, we agree that the mean of the highest 5 percent value determined from sequences of Fourier analyses for each revolution is a better choice, and it has been the most frequently suggested average value for correlation purposes on the basis of several investigations by SSPA. Figures 39 and 55 present the mean of the highest 5 percent of the model pressure amplitudes that may be directly compared with the analytical predictions shown in Fig. 39.

Mr. Noonan commented that the main efforts of the program outlined in this paper were directed toward the identification, verification, and reduction of the source of propeller-excitation, and not on classical noise reduction methods. This was certainly the case. We chose both wake and propeller modification alternatives. Anyway, it is most likely that the available noise reduction techniques would have helped little or not at all in the low frequency range that characterizes the worst noise levels of the AO-177. There may be some additional gains that could be made by selectively stiffening certain structural elements in the after part of the ship in order to alter the susceptibility of the hull to the transmission of vibration energy to interior compartments. Mr. Noonan also argued for criteria for evaluating the surface force aspect of propeller excitation for proposed designs, and we certainly agree. In fact, because of the AO-177 experience we are trying to fill this need.

Mr. Noonan requested comment on the correlation of cavitation inception from model and full-scale observations. Inception of cavitation usually refers to the velocity conditions (rpm and ship speed) at which cavitation of a particular type first appears. Inception by itself is not an issue in the present situation. Inception of cavitation occurs at much lower speeds than the regime of excessive excitation which is a result of fully developed, sheet cavity flow experiencing periodic instability and collapse. The important cavitation scaling aspects are the scaling of the cavity volume dynamics and unsteady cavity flow patterns as they relate to the propeller excitation levels. Dr. Stern also expressed interest in this latter issue. Correlation of model and full scale results in this area is very complicated, involving topics such as scaling model to full scale wake, the boundary condition simulated by the tunnel ceiling, ambient flow quality, and air content. On the basis of cavitation extent and general cavity appearance, the water tunnel results correlate fairly well with patterns observed full scale. The most current discussion of the subject of correlation with large water tunnel experiments is given by Breslin et al. [60]. Regardless of the assessment of the absolute levels of pressure pulse results from SSPA, we have interpreted the results of the water tunnel tests from a point of view of relative magnitudes. That is, we defined the final choice of a design option on the basis of best relative improvement over the case of the unmodified AO-177.

Dr. Stern stated a desire for a more complete review of the computational results accumulated in the course of this project. We agree that this would be interesting and useful. Unfortunately, the length of this paper limited the attention that could be given to the analytical results. We hope to include a more complete discussion of the computational results in a future reference. In this connection, Dr. Stern offered his computed results for the AO-177 unsteady volume velocity and estimated pressure pulse amplitudes. We thank him for this contribution.

We thank Mr. Byers for his thoughts on the steps being undertaken to avoid the recurrence of problems similar to those encountered by the AO-177.

The details of the fin structural design and the fin installation program provided by Messrs. Arntson, Ikeda, and Lusick are certainly timely and an important addition to this paper. We thank these discussers for their remarks.

Prof. Breslin and Dr. McKee presented calculations for the AO-177 without fin from the combination of computer programs from MIT and DL-SIT for the cavitating propeller and hull-propeller interaction analysis, respectively. They provided a comparison between the predicted pressure pulse amplitudes and the mean of the highest 5 percent amplitudes measured in the cavitation tunnel at SSPA. As noted previously, we agree that the average of the 5 percent highest amplitudes is probably the preferred experimental quantity for correlation. We thank the discussers for this additional information.

Dr. Hylarides raised some interesting points and challenging questions. Based on information available in the paper or inferred from his experience, he suggested a reordering of the corrective options for solving the problems of the AO-177. He reiterated the idea that for reducing the levels of interior noise any design modification should be directed toward the reduction of the higher harmonics of the induced pressure pulses. We have previously stated this aim, but we should note that other considerations also played a role in the final choice of fin design. To shed more light on the comparison between the two fin configurations, we include in Fig. 54 the pressure amplitude spectra measured at the forwardmost point (Point A, centerline), for the unmodified hull and for each of the fins at the full-power, full load condition. These curves represent the model scale pressure pulse levels (rms) expressed in dB versus the frequency for the model scale. These data are considered reliable up to about 1600 Hz. Here we see that both fins reduced the general levels of higher frequency pressure pulses. In the lower frequency range (up to seven times the blade rate frequency, 82 Hz full scale), the tunnel fin produced the larger reductions, but for the higher harmonics the bigger reductions were associated with the flow accelerating fin. From this comparison, we feel that neither fin shows clear superiority considering the entire frequency range of interest. It appears that either fin probably would have reduced the inboard noise.

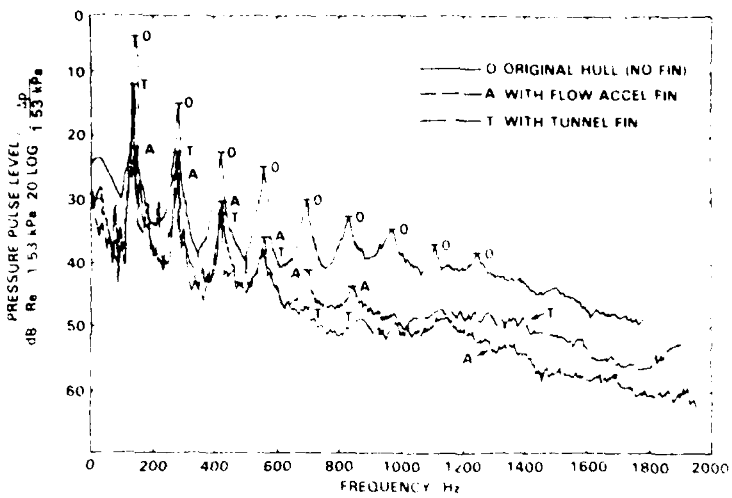


Fig. 54 Model scale pressure amplitude spectra measured at forwardmost transducer A comparing cases without and with the two fins

With regard to the selection of a corrective option, there was a distinct need to choose a fix that could be implemented quickly and inexpensively. Since initial fin designs were ready by the time of the cavitation tunnel tests, a fin could be installed on the ship faster than any other option. If the choice had been a new propeller, it would have required approximately one year longer to have a verified design modification ready to be installed on the ship. The better performance of the flow-accelerating fin relative to the tunnel fin in reducing blade rate periodic pressures, especially forward and aft of the tip plane, was the principal appealing feature. Secondary advantages are that the flow-accelerating fin is smaller, lighter, and cheaper to build and install. Its added drag is smaller as well. Criticism of using the SSPA criterion beyond its intended scope (hull vibration) is probably justified here, but we believe that this criterion correctly indicated that there was a greater margin of safety for avoiding possible hull girder vibration problems with the flow-accelerating fin than with the tunnel fin. More significantly, the flow-accelerating fin produced lower blade rate pressure amplitudes over the tip, while the tunnel fin produced slightly higher values (mean of 5 percent highest amplitudes) compared with the case of the unmodified hull. In light of Dr. Hylarides's argument about the desirability of having reduced pressure pulse amplitudes with a fin, presumably over the tip, it seems difficult to justify a firm conviction that the tunnel fin would have been such an obviously better choice.

All things considered, we felt that the choice between the two fins was rather close. It is perhaps an academic point since the full-scale fin evaluation trial showed that the flow-accelerating fin was a satisfactory and sufficient correction to the problems of the AO 177.

Again, the authors wish to thank all of the discussers for their significant contributions to this paper.

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